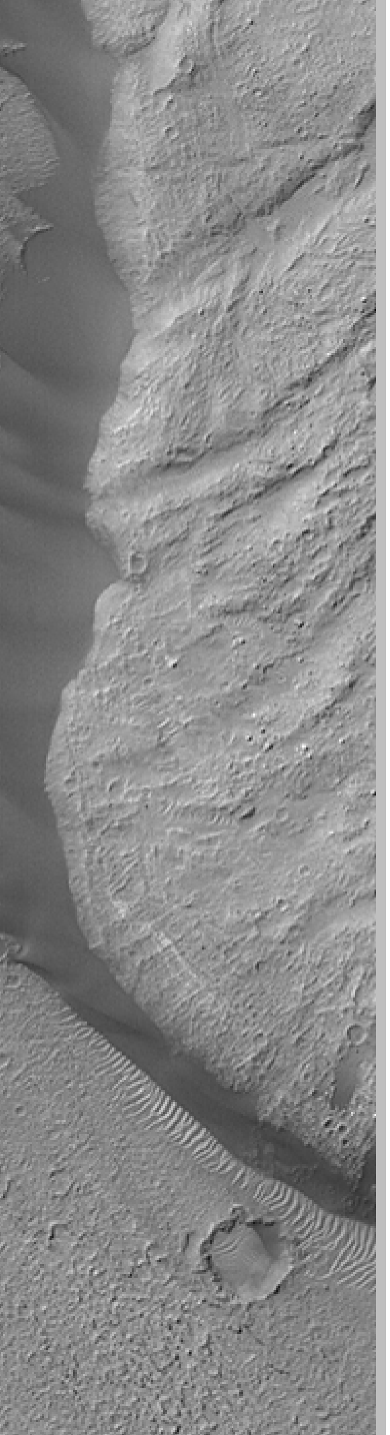


Mars Science Laboratory
FY04 Year End Review

MSL Focused Technology

102159 – 09.03.05.02
Rover Technology TB (incl CLARAty)

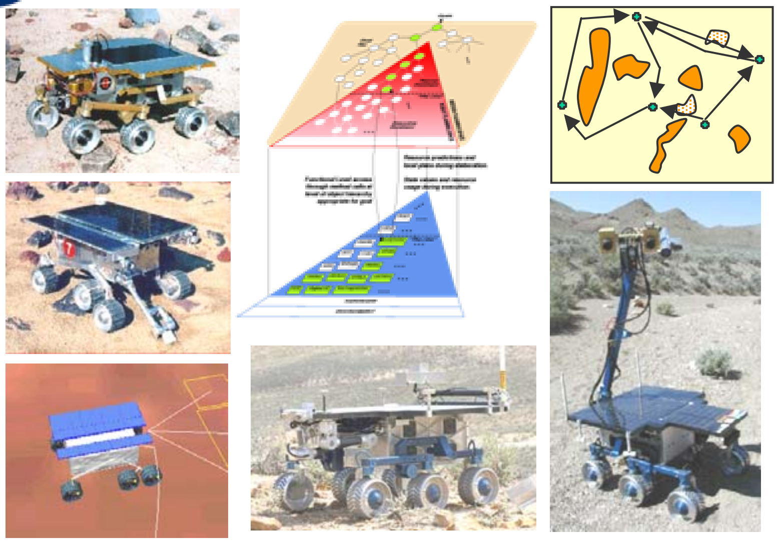
Issa A.D. Nesnas
October 15, 2004

Presentation Outline

- CLARAty overview
- Schedule and milestones
- Team, collaborations, and processes
- Significant events
  - Level I – framework for single-cycle instrument placement
  - Level II – framework for comparing multiple pose estimators
- Deliverables and technical progress
- CLARAty test bed

CLARAty Overview

Rover Technology TB (incl CLARAty)



Objectives:

- Facilitate infusion of performance-enhancing navigation and manipulation technologies into MSL flight system
- Provide a flexible framework for integrating and comparing competing technologies on all research rovers: Rocky8, FIDO, Rocky7, K9, and FIDO5

Task Manager:

Issa A. D. Nesnas (818) 354-9709
nesnas@jpl.nasa.gov

Participating Organizations:

JPL, Ames Research Center, Carnegie Mellon, U. of Minnesota, RMSA Universities

Facilities:

Rocky 8, FIDO, Rocky 7, K9, FIDO 5, ATRVs, CLARAty test bed, ROAMS, Maestro, JPL Mars Yard

Funding Profile ($K):

FY 03	FY 04	FY 05	FY 06
1,379	1,394	1,000	400

FY03-FY05 Milestones:

FY03 mobility and navigation for long traverse

FY04 pose estimation, tracking, and manipulation for instrument placement

FY05 complete simulations, onboard science and health monitoring

Problem Statement

- **Problem:**
  - **Lack** of **integrated** and **validated** robotic technologies for infusion into flight
  - **Redundant** infrastructure for each robotic project
  - **No framework** to capture technologies from universities
  - **No interoperable** software among: Rocky 8, FIDO, Rocky 7, K9, ATRVs

- **Key Challenges**
  - Different physical characteristics for robots
  - Different hardware architecture for rovers
  - Collaborative multi-center software development
  - Flexible framework for advanced research
  - Working software for all platforms
  - Customer support
  - Rover access to remote developers
  - Software access and intellectual property
  - Legacy code bases

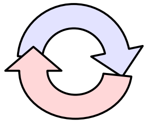
Mission Relevance and State-of-the-Art

- **Mission Relevance**
  - Enables integration and validation of competing technologies
  - Enables technology transfer to flight from a **single** integrated source
  - Captures university technologies for future missions
  - Makes research rovers viable test bed for flight
  - Easily adapts to future rovers with different hardware architectures
  - Relevant to MSL, AFL, and MSR missions; and lunar robotic missions

- **State-of-the-art**
  - Mainly separate disparate robotic software systems within NASA
  - Interoperability limited to high-level encapsulation
  - Several efforts seeking common infrastructure – MDS, DARPA (Jaus), Intel (Robotics Engineering Task Force)

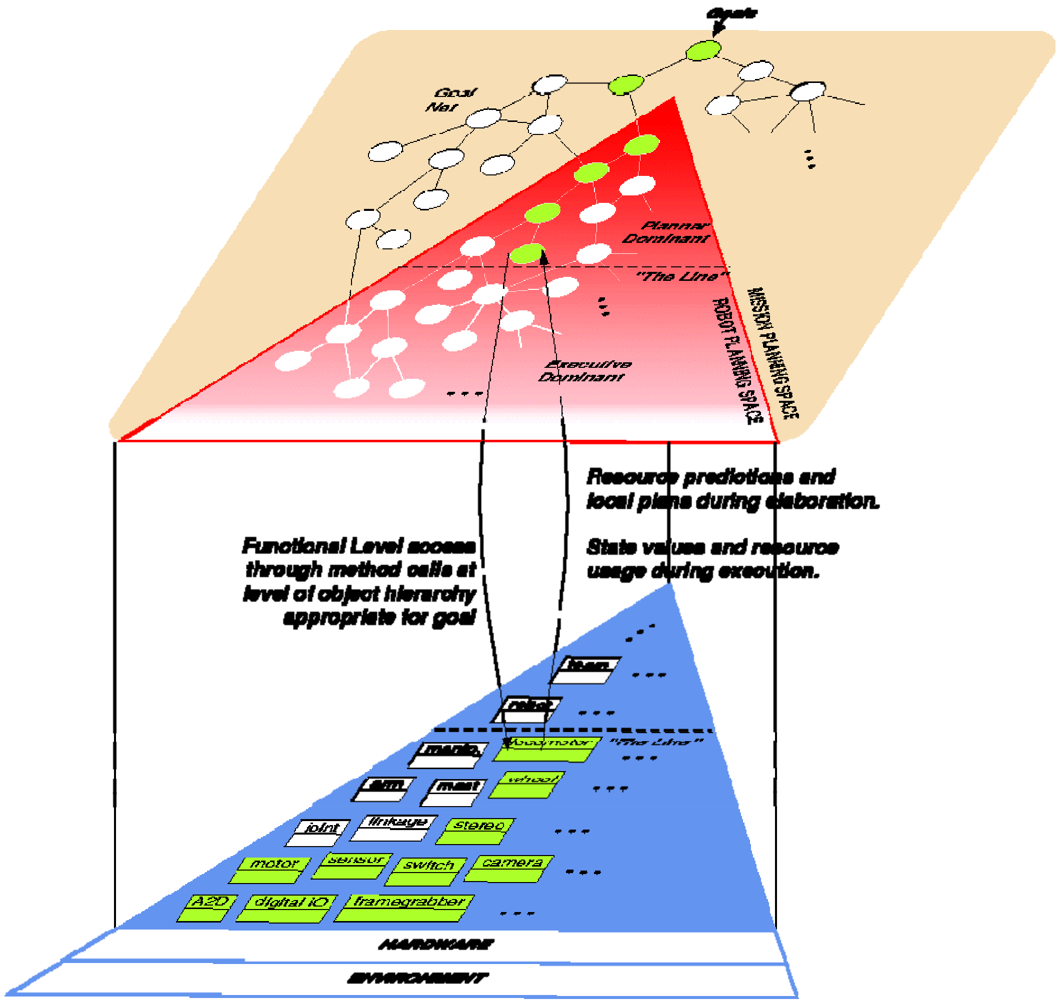
Technical Approach

- Use **global perspective** on various domains (motion, vision, estimation, navigation)
- Identify **recurring patterns** and **common infrastructure** therein
- Use **domain expertise** to guide design
- Define **proper interfaces** for each subsystem
- Develop **generic framework** to support various implementations
- **Adapt** legacy **implementations** to validate framework
- **Encapsulate** when re-factoring is not feasible or affordable
- **Test** on multiple robotic platforms and study limitations
- **Feed** learned experience **back** into the design
- **Review** and **update** to address limitations



After several iterations one hopes to have achieved a truly reusable infrastructure

A Two-Layered Architecture



THE DECISION LAYER:
Declarative model-based global planning and scheduling

INTERFACE:
Interactions at various levels

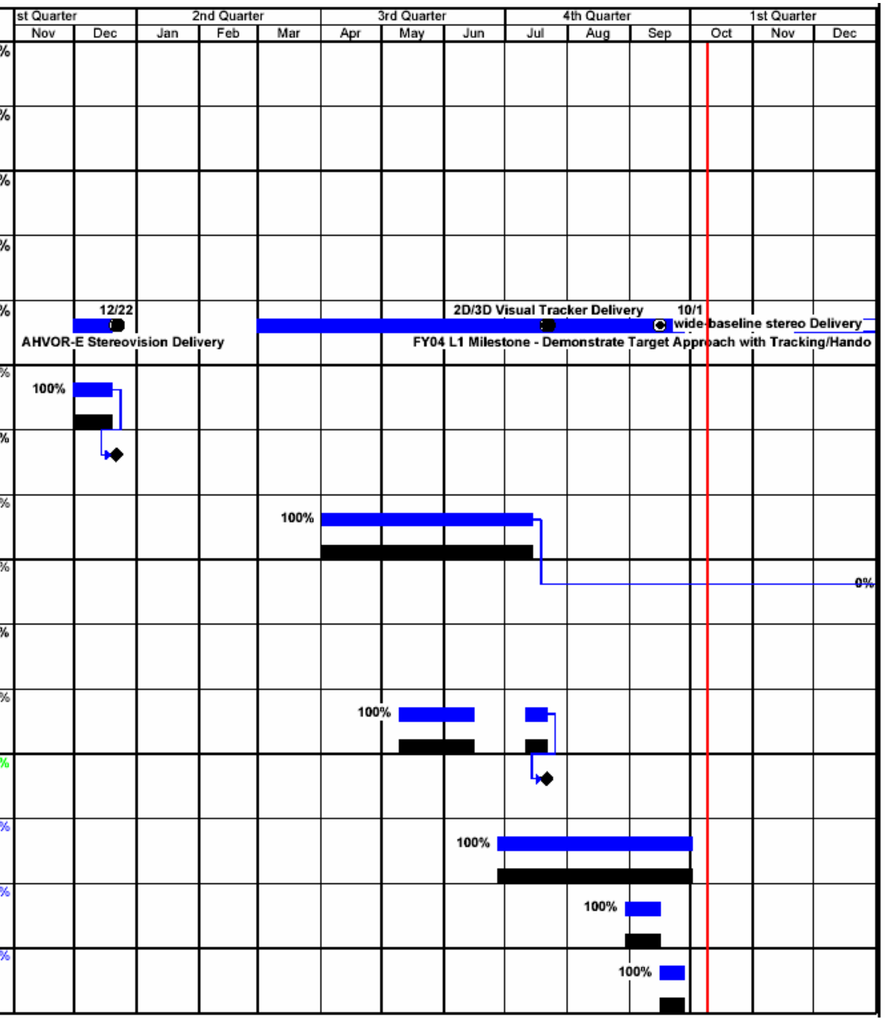
THE FUNCTIONAL LAYER:
Object-oriented abstractions for robotic capabilities

System Adaptation

Schedule and Milestones

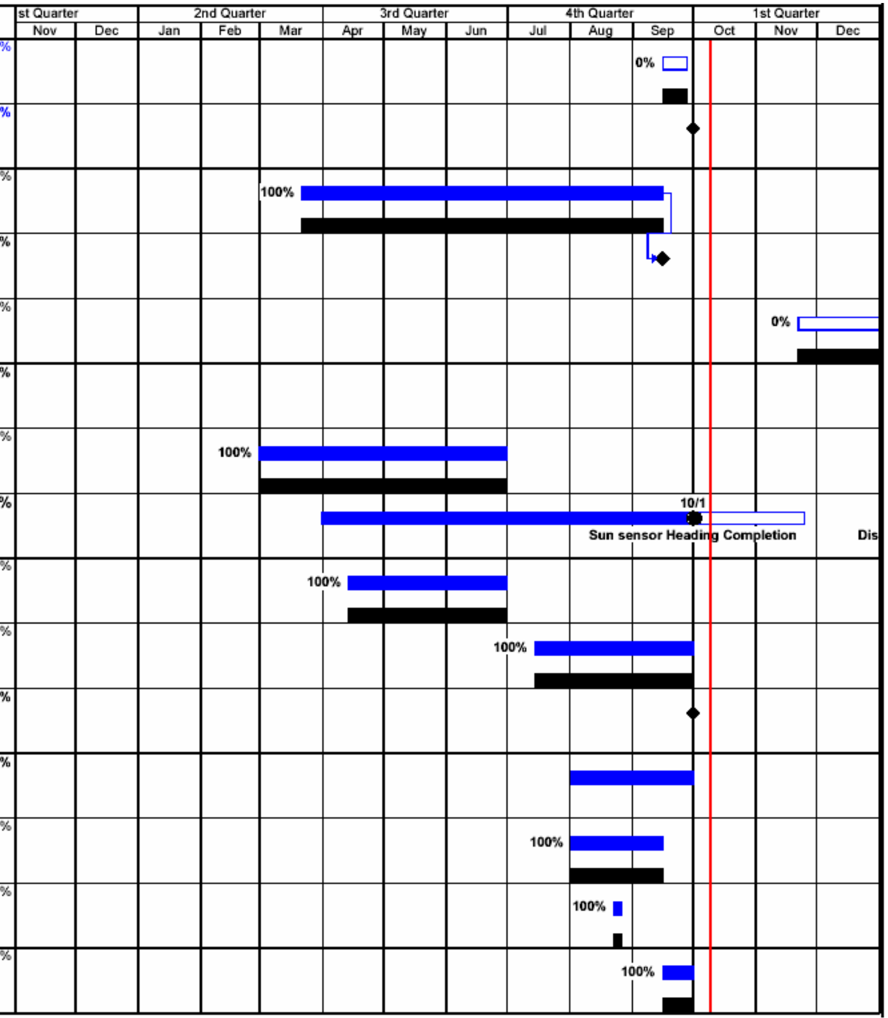
Schedule (1/5)

ID	WBS	Name	% Complete
40	MSL.09	**MSL Technology**	**36%**
852	09.03	**Rover Technology**	**34%**
1000	09.03.05	**Rover Tech Integration**	**58%**
1001	09.03.05	**CLARAty**	**58%**
1002	09.03.05	**vision**	**76%**
1003	09.03.05	Stereovision with CAHVOR-E models	100%
1004	09.03.05	CAHVOR-E Stereovision Delivery	100%
1005	09.03.05	Multi-view registration on Rocky 8	100%
1006	09.03.05	Multi-view registration version 2 on Rocky 8	0%
1007	09.03.05	Multi-view registration Delivery	0%
1008	09.03.05	Integrated 2D/3D Visual Tracker on Rocky 8	100%
1009	09.03.05	2D/3D Visual Tracker Delivery	100%
1010	09.03.05	2D/3D Visual Tracker Validation Support	100%
1011	09.03.05	Integrate visual tracking with obstacle avoidance	100%
1012	09.03.05	Integrate and test visual tracking and camera handoff	100%



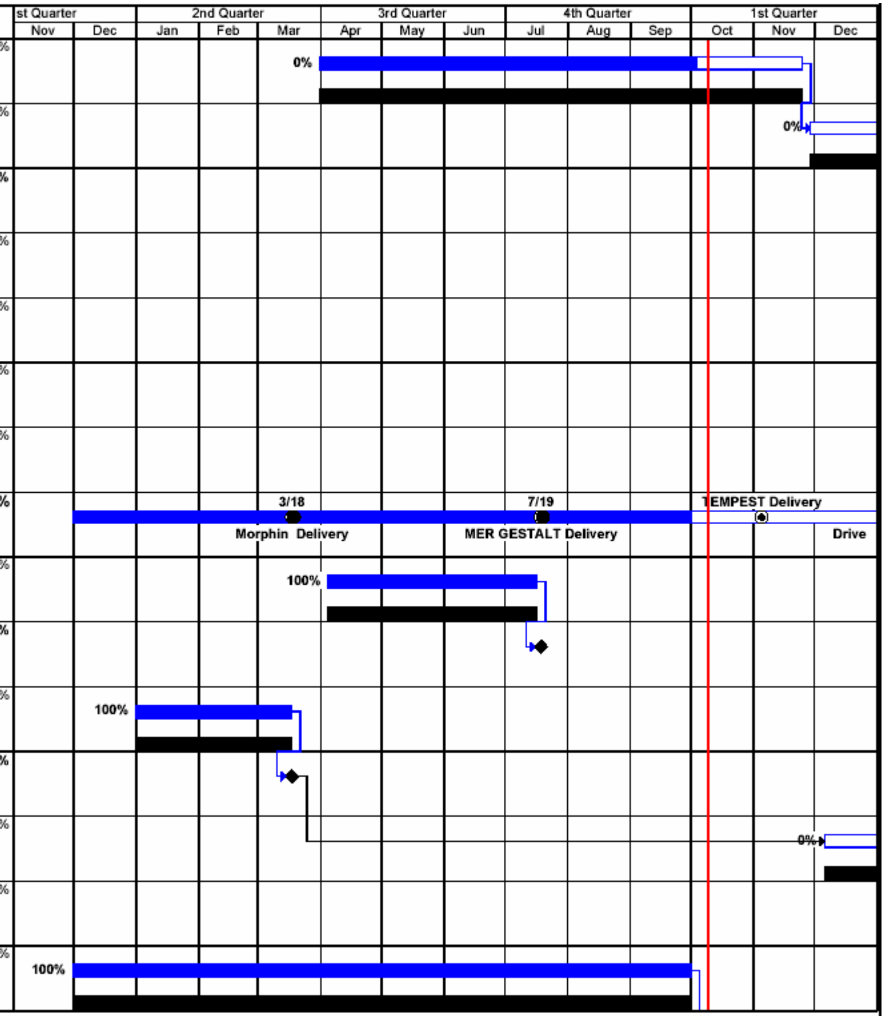
Schedule (2/5)

ID	WBS	Name	% Complete
1013	09.03.05	Refine close tracking with hazcams	0%
1014	09.03.05	FY04 L1 Milestone - Demonstrate Target Approach with	100%
1015	09.03.05	wide-baseline stereo	100%
1016	09.03.05	wide-baseline stereo Delivery	0%
1017	09.03.05	Mesh registration for camera handoff	0%
1018	09.03.05	Mesh registration Delivery	0%
1019	09.03.05	Visual Sinkage Estimation (Dubowsky)	100%
1020	09.03.05	estimation	39%
1021	09.03.05	Sun sensor absolute heading estimator with locomotio	100%
1022	09.03.05	Re-implement centroid software and retest	100%
1023	09.03.05	Sun sensor Heading Completion	100%
1024	09.03.05	FY04 L2 Milestone	100%
1025	09.03.05	Implement Sojourner and Rocky 7 pose estimation (	100%
1026	09.03.05	Collect data for comparing four estimators (Sojourn	100%
1027	09.03.05	Compare performance of four pose estimators	100%



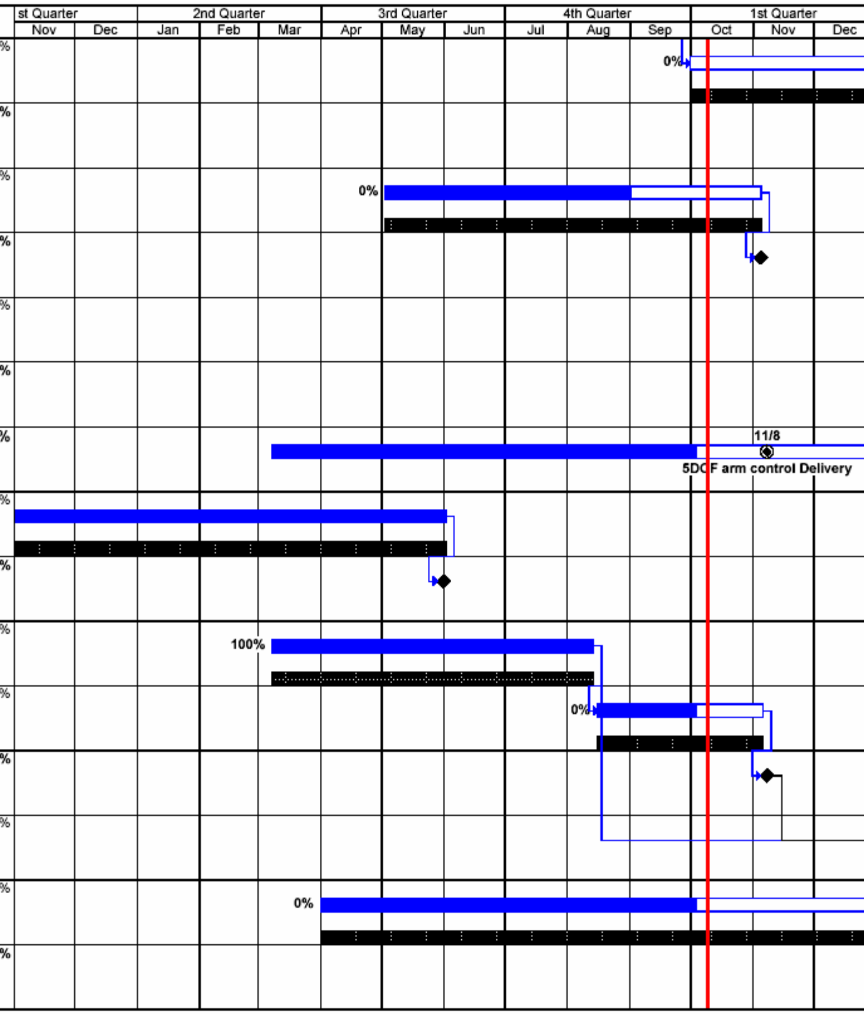
Schedule (3/5)

ID	WBS	Name	% Complete
1028	09.03.05	Discrete 6DOF KF with sun sensing integration	77%
1029	09.03.05	Discrete 6DOF KF with sun sensing test and tune	0%
1030	**09.03.05**	**Discrete 6DOF KF with sun sensing delivery**	**0%**
1031	09.03.05	FlexNav Position Estimator (Borenstein)	0%
1032	09.03.05	Motor Fault Detection (Dearden)	0%
1033	09.03.05	Terrain Classification (Dubowsky)	0%
1034	09.03.05	Terrain Classification (Pedersen)	0%
1035	**09.03.05**	**navigation**	**57%**
1036	09.03.05	Encapsulated MER GESTALT on FIDO	100%
1037	**09.03.05**	**MER GESTALT Delivery**	**100%**
1038	09.03.05	Morphin navigator on FIDO	100%
1039	**09.03.05**	**Morphin Delivery**	**100%**
1040	09.03.05	Morphin navigator with visual odometry	0%
1041	09.03.05	Morphin navigator with in ROAMS	0%
1042	09.03.05	Drivemaps navigator encapsulation	100%



Schedule (4/5)

ID	WBS	Name	% Complete
1043	09.03.05	Drivemaps navigator on FIDO	0%
1044	09.03.05	Drivemaps Delivery	0%
1045	09.03.05	TEMPEST / ISE (Stentz)	65%
1046	09.03.05	TEMPEST Delivery	0%
1047	09.03.05	Slope Navigator (Helmick)	0%
1048	09.03.05	Slope Navigator Delivery	0%
1049	09.03.05	manipulation	67%
1050	09.03.05	LM629 Motion Control Board Development and Testing	100%
1051	09.03.05	LM629 Motion Control Board Delivery to MSL Manipula	100%
1052	09.03.05	5DOF arm control framework	100%
1053	09.03.05	5DOF arm control and straight line trajectory on FIDO	58%
1054	09.03.05	5DOF arm control Delivery	0%
1055	09.03.05	CLARAty/ROAMS with manipulation	0%
1056	09.03.05	Arm collision prediction for 5DOF in new manip framw	46%
1057	09.03.05	Arm collision prediction Delivery	60%



Schedule (5/5)

Responsible: Gabrial Udomkesmalee

Mars Science Laboratory

Focused Technology Schedule (FY Calendar)

Schedule Analyst: S.Gillespie
Status Date Fri 10/8/04
DRAFT Fri 10/8/04

ID	WBS	Name	% Complete	st Quarter		2nd Quarter			3rd Quarter			4th Quarter			1st Quarter		
				Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1058	09.03.05	**rover base placement with obstacles**	40%														
1059	**09.03.05**	**rover base placement with obstacles Delivery**	**0%**														

Accomplishments—Past Period

October 2003 to September 2004

Planned	Accomplished
1. Deliver for validation:	**1. Deliver for validation:**
• Stereovision with CAHVORE to IP	• **Complete**
• Visual target tracking to IP	• **Complete** – delivered for Rocky 8
• Morphin navigator to LT	• **Complete** – delivered for FIDO
2. Deliver LM629 motion control board to MSL manipulation task	2. **Complete** – tested hardware/software and delivered
3. Integrate and Test:	**3. Integrate and Test:**
• MER GESTALT navigator (MER)	• **Complete** – tested with ROAMS
• Drivemaps navigator (FIDO legacy)	• **Complete** – encapsulated and tested in simulation
• Wide baseline stereo (U. Washington)	• **Complete** - tested on Rocky 8 in Mars Yard
• Mesh registration / camera hand-off (Ohio State)	• **Complete** – tested with Rocky 8 images
• Wheel visual sinkage (MIT)	• **Complete** – tested with MIT test bed images only
4. Implement and test elements of 6DOF EKF (U. of Minnesota)	4. **Complete** – tested on Rocky 8 and FIDO
5. Develop generic manipulation infrastructure	5. **Completed** 5DOF infrastructure – generic one underway
6. Fix sun sensor implementation	6. **Complete** – re-implemented algorithms

and much more …

IP – Instrument Placement Validation task
LT – Long-range Traverse Validation task

Action Item Status

FY03 Year End AI	Status
MTP Board Recommendation #3: The board recommends that JPL pursue open source status for CLARAty.	• Identified necessary steps to prepare CLARAty for open source. • Identified the modules necessary for open source release. • Provided feedback to program office on alternatives for critical non-releasable modules. • Started a collaboration with CMU-West to investigate low-cost rover hardware platforms. • Supporting new RoverWare software dissemination task.

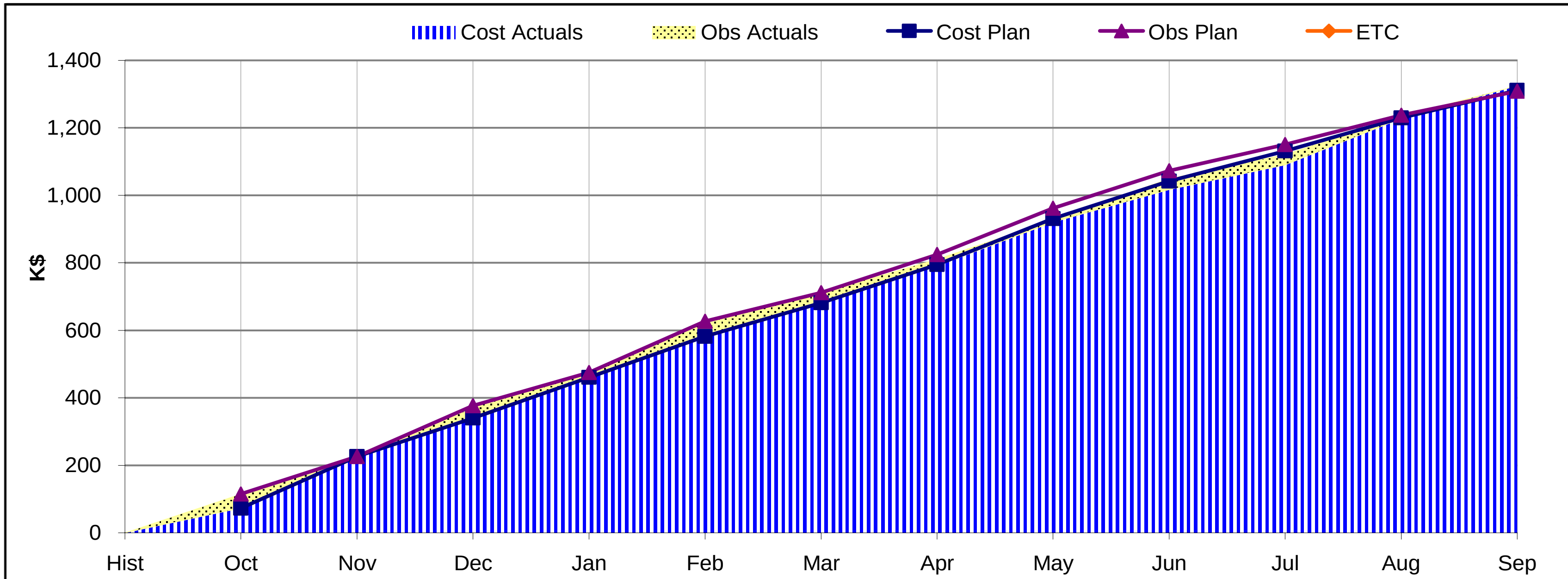
Issues and Resolutions

Issue Description	Solution Options/Schedule
1. Limited number of rover platforms.	1. Increase by refurbishing or building new rovers.
2. Intellectual Property and sharing of software among NASA centers and universities.	2. Setup a consortium of all centers involved and draft a license agreeable to the consortium.
3. Difficult and expensive to retain staff with a wide technical base and interest in supporting technologies developed by others.	3. One or more: • Reduce scope of CLARAty. • Attract members who are generalists and have interest in working across disciplines. • Increase funding to retain diverse staff.

Financial Status

FINANCIAL

SEP FY04 YTD



YTD	Hist	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ETC													
Cost													
Plan		73	226	340	460	582	681	795	931	1,042	1,131	1,230	1,312
Actuals		73	226	340	460	582	681	791	920	1,017	1,090	1,227	1,325
Variance		**0**	**0**	**0**	**0**	**0**	**0**	**4**	**11**	**25**	**42**	**3**	**(13)**
Obs													
Plan		115	227	377	475	627	712	825	962	1,073	1,151	1,238	1,309
Actuals*		115	227	377	475	627	712	811	928	1,049	1,121	1,234	1,310
Variance		**0**	**0**	**0**	**0**	**0**	**0**	**14**	**34**	**23**	**30**	**4**	**(1)**

*Includes estimated burden on encumbrance

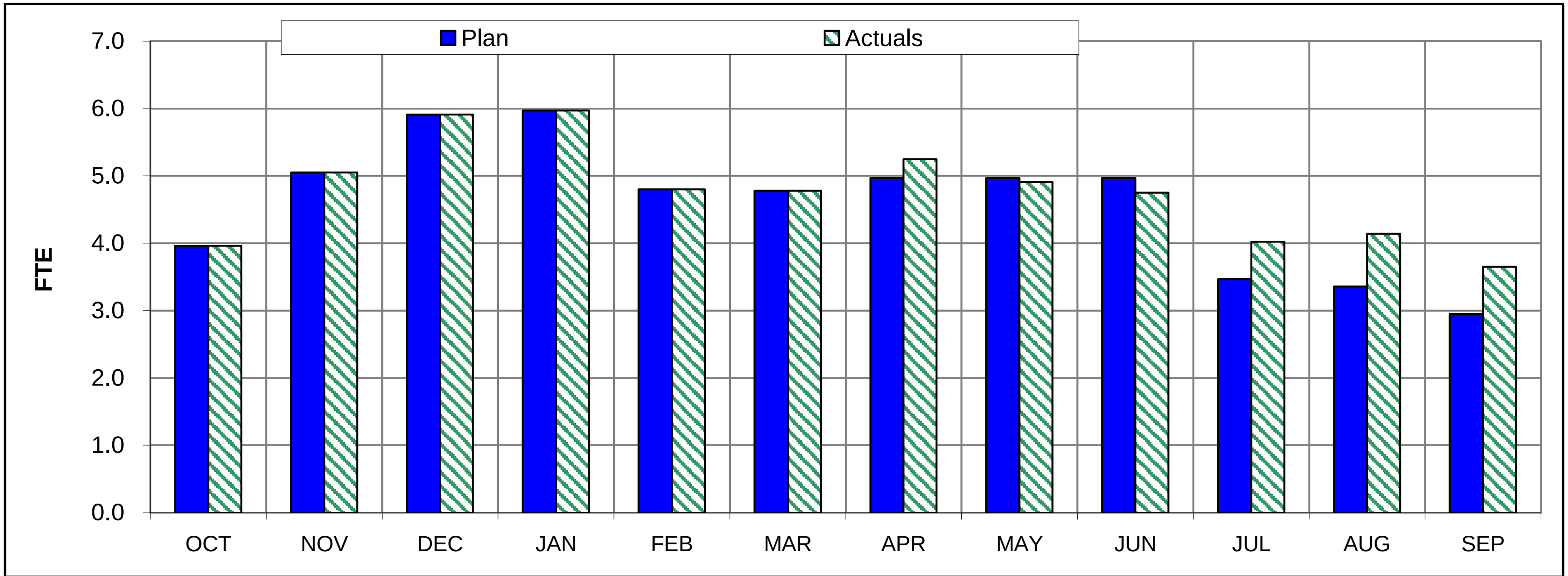
Variance Thresholds: **= +/- < 5%** **= +/- 5% to 10%** **= +/- > 10%**

Workforce Status

102159-09.03.05.02 CLARAty for MSL

WORKFORCE

SEP FY04



	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
MTD Plan												
Total Plan (JPL+CTR)	4.0	5.1	5.9	6.0	4.8	4.8	5.0	5.0	5.0	3.5	3.4	3.0
MTD Actuals												
Total Actuals (JPL+CTR)	4.0	5.1	5.9	6.0	4.8	4.8	5.3	4.9	4.8	4.0	4.1	3.7
Variance	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**(0.3)**	**0.1**	**0.2**	**(0.5)**	**(0.8)**	**(0.7)**

Variance Thresholds: **= +/- < 5%** **= +/- 5% to 10%** **= +/- > 10%**

Status Summary

Technical

JUNE	JULY	AUG	SEPT
G	G	G	G

Schedule

JUNE	JULY	AUG	SEPT
G	Y	G	G

Resources

JUNE	JULY	AUG	SEPT
G	G	G	G

Detailed Description: (for items identified as yellow or red)

- Schedule and resources are on track

G	No current problem All commitments can be met	Y	Major problem Identified solution Commitment is in jeopardy	R	Major problem No identified solution Commitment cannot be met

Planned Accomplishments – FY05

- **Prepare technologies for validation based on MSL needs**
- **Start interactions with new NRA awardees**

Date	To	Delivery Description
12/04	IP	Tracking with panoramic and navigation cameras
1/04	LT	GESTALT navigation with ROAMS
3/04	IP	Navigation to Hazard camera tracking and hand-off
4/05	LT	GESTALT navigation on Rocky 8
6/05	IP	Stereo-based manipulation and rover-base placement
9/05	IP	Collision detection for manipulation

LT – Long-range Traverse Validation
IP – Instrument Placement Validation

Team, Collaborations, and Processes

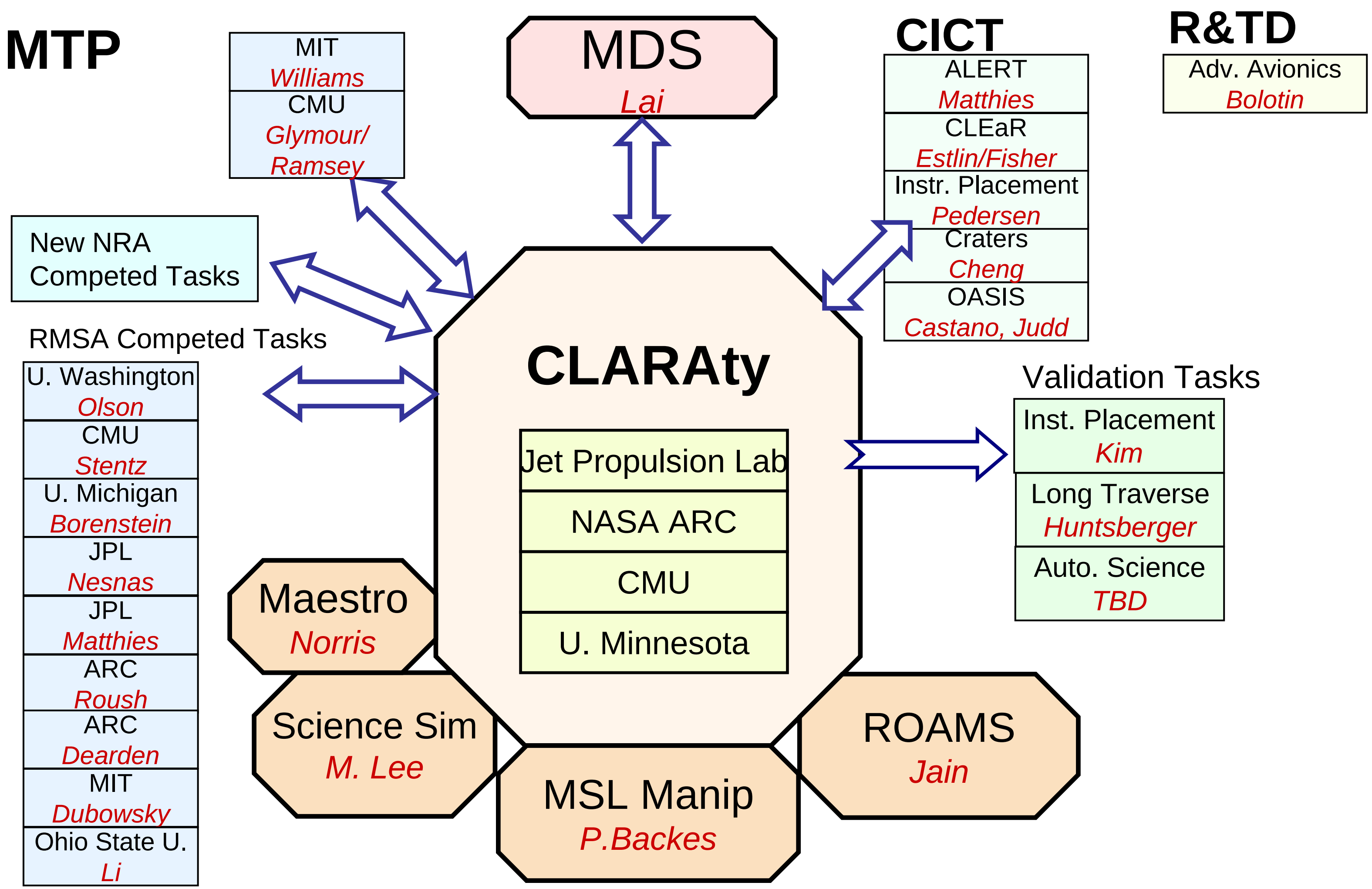
Highlights

- A Challenging Year for CLARAty
  - Delivered **four** major algorithms for validation
  - Captured **six** major legacy and competed algorithms
  - Supporting **four** major platforms
  - Maintaining a **large** number of algorithms
  - Lost several key staff members (medical leave, MER support, etc.)
- Development Process
  - Setup a new development process but needs further tuning
  - Started an automated night build process
  - Improved CLARAty test bed
- Formalizing manipulation infrastructure (requirements document)
- Participated in several Code T ICP and ECP – awarded two ICPs that will leverage CLARAty
- Presented invited paper at IROS
- Presented papers at Aerospace Conference

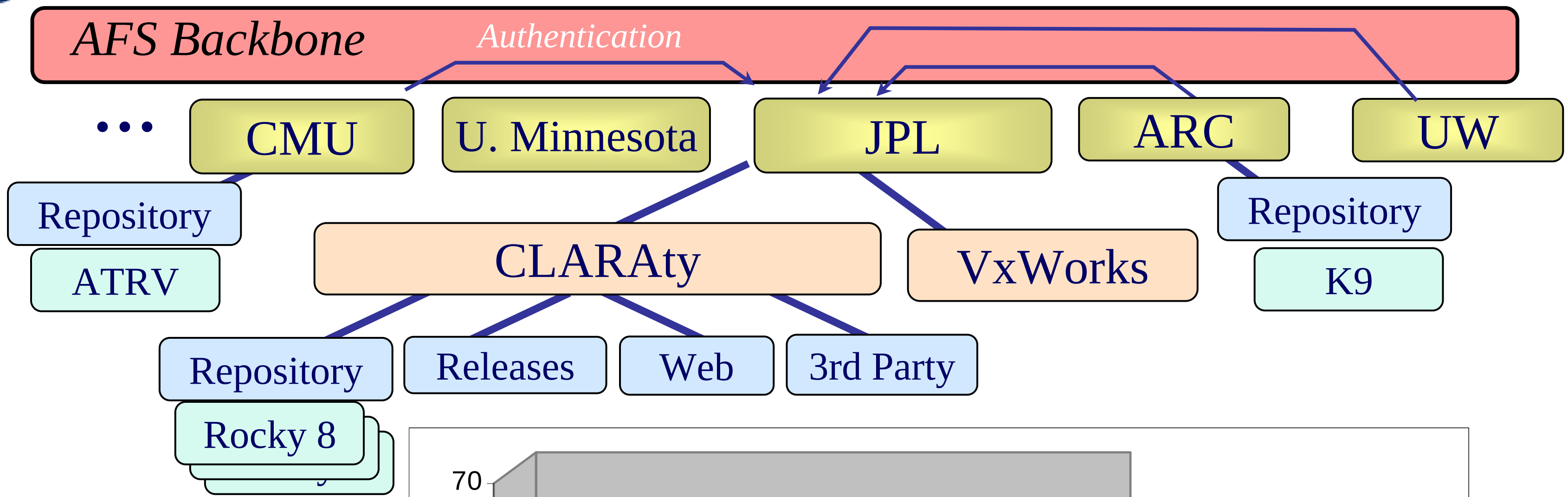
CLARAty Core Team

- **NASA Ames Research Center**
  - Maria Bualat
  - Clay Kunz (*Data Structure Lead*)
  - Eric Park
  - Susan Lee
  - Anne Wright *(Cog-E & Core lead)*
- **Carnegie Mellon University**
  - David Apelfaum
  - Reid Simmons *(Navigation lead)*
- **University of Minnesota**
  - Stergios Roumeliotis
  - Yukikazu Hidaka
- **Jet Propulsion Laboratory**
  - Max Bajracharya (34) *(Cog-E & Vision lead)*
  - Edward Barlow (34)
  - Antonio Diaz Calderon (34)
  - Caroline Chouinard (36)
  - Daniel Clouse (34)
  - James Dillon (34)
  - Tara Estlin (36) *(Deputy & Decision Layer lead)*
  - Erann Gat (36)
  - Dan Gaines (36) *(Estimation Lead)*
  - John Guineau (34)
  - Mehran Gangianpour (34)
  - Won Soo Kim (34) *(Motion lead)*
  - Richard Madison (34)
  - Michael Mossey (31)
  - Issa A.D. Nesnas (34) *(Task Manager)*
  - Richard Petras (34) *(Adaptation lead)*
  - Babak Sapir (31)
- **OphirTech**
  - Hari Das Nayar

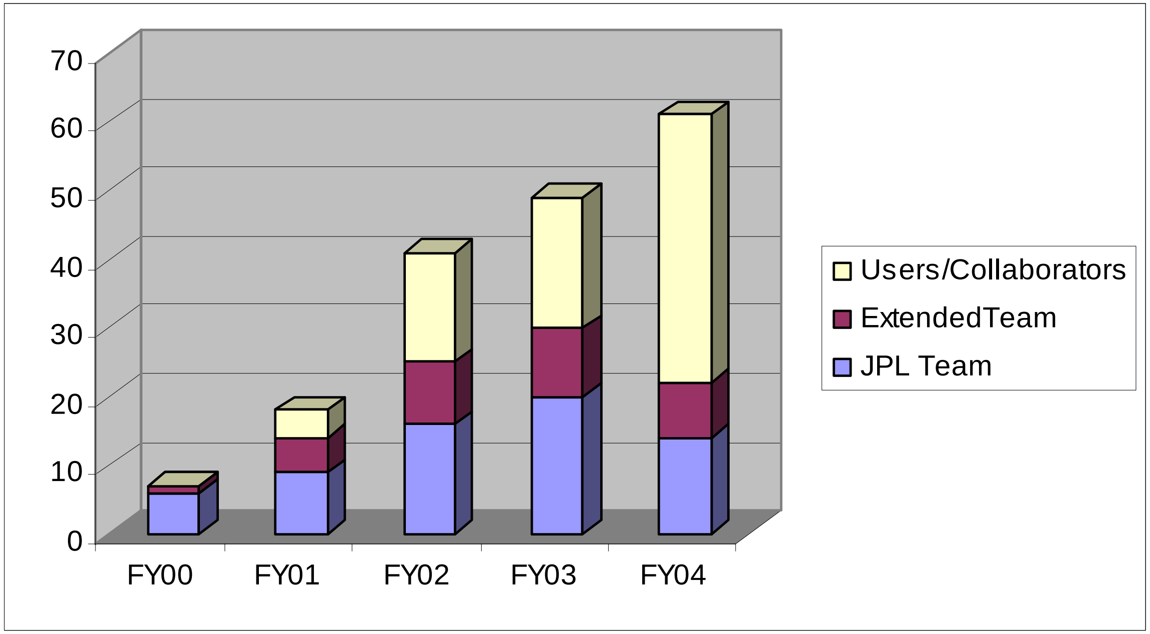
Collaborations



Software Development Process

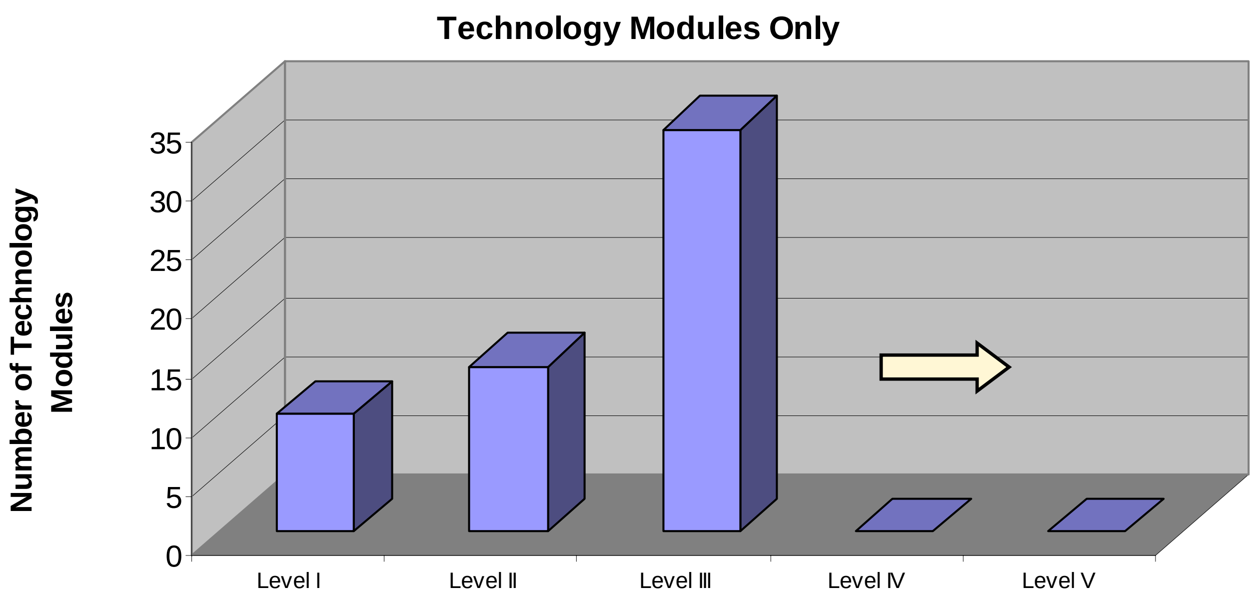


Number of employees and not FTEs



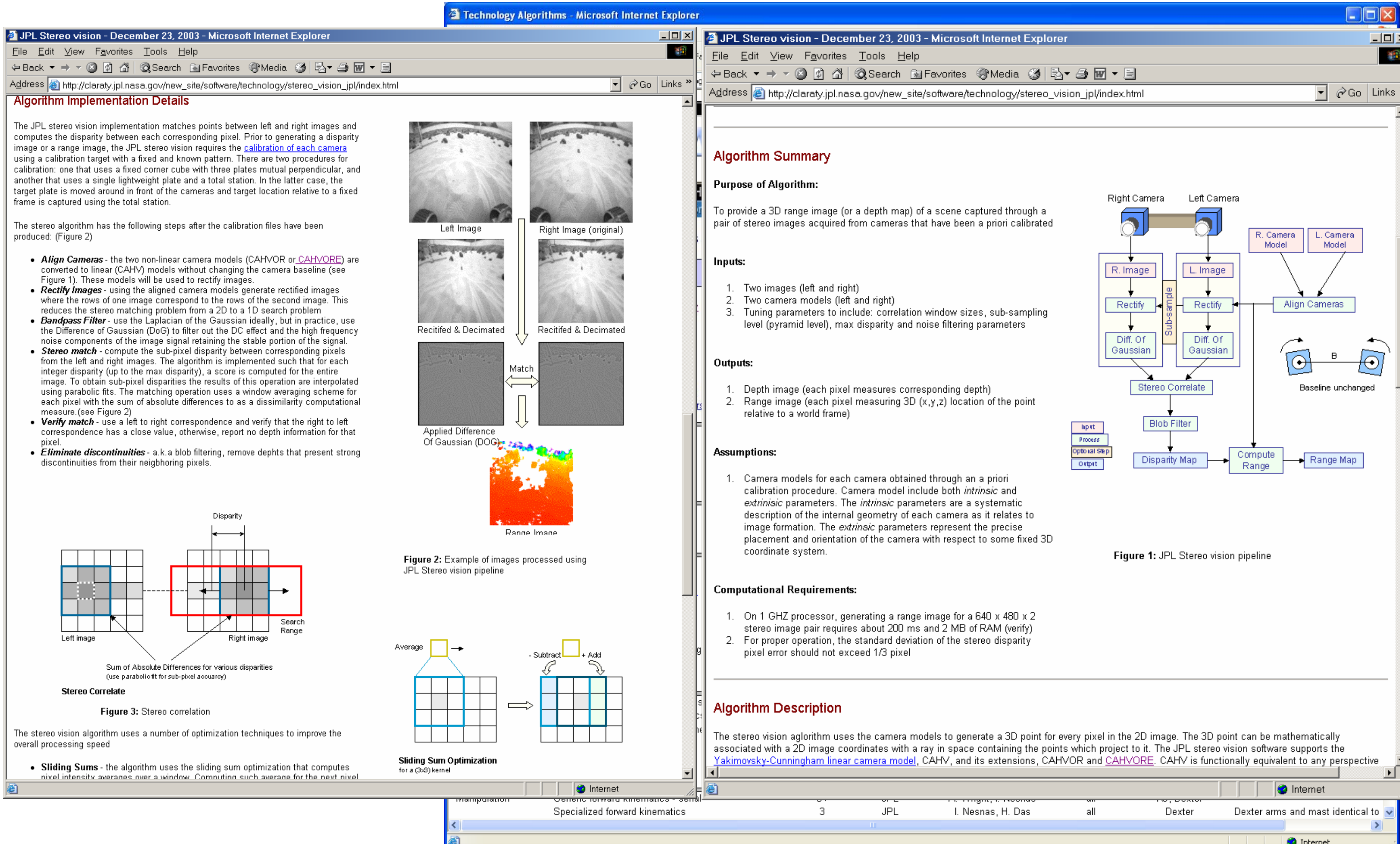
Some CLARAty Statistics

- ~320 modules in repository (increase of 6% from FY03) – goal is to limit modules
- ~60 modules are researched technology algorithms (~20%)
- About 500,000 lines of C++ code – revise and reduce
- Five adaptations: Rocky 8, FIDO, Rocky 7, ATRV, K9
- Most technology modules are at Level III
- None are at Level IV or Level V (formally reviewed, documented, and open source)



CLARAty Integration Levels
- Level I – Deposited
- Level II – Encapsulated
- Level III – Refactored
- Level IV – Formally reviewed
- Level V – Open source and fully documented

Technology Algorithms in CLARAty



Technology Algorithms - Microsoft Internet Explorer

JPL Stereo vision - December 23, 2003 - Microsoft Internet Explorer

http://claraty.jpl.nasa.gov/new_site/software/technology/stereo_vision_jpl/index.html

Algorithm Implementation Details

The JPL stereo vision implementation matches points between left and right images and computes the disparity between each corresponding pixel. Prior to generating a disparity image or a range image, the JPL stereo vision requires the calibration of each camera using a calibration target with a fixed and known pattern. There are two procedures for calibration: one that uses a fixed corner cube with three plates mutual perpendicular, and another that uses a single lightweight plate and a total station. In the latter case, the target plate is moved around in front of the cameras and target location relative to a fixed frame is captured using the total station.

The stereo algorithm has the following steps after the calibration files have been produced: (Figure 2)

- ***Align Cameras*** - the two non-linear camera models (CAHVOR or CAHVORE) are converted to linear (CAHV) models without changing the camera baseline (see Figure 1). These models will be used to rectify images.
- ***Rectify Images*** - using the aligned camera models generate rectified images where the rows of one image correspond to the rows of the second image. This reduces the stereo matching problem from a 2D to a 1D search problem
- ***Bandpass Filter*** - use the Laplacian of the Gaussian ideally, but in practice, use the Difference of Gaussian (DoG) to filter out the DC effect and the high frequency noise components of the image signal retaining the stable portion of the signal.
- ***Stereo match*** - compute the sub-pixel disparity between corresponding pixels from the left and right images. The algorithm is implemented such that for each integer disparity (up to the max disparity), a score is computed for the entire image. To obtain sub-pixel disparities the results of this operation are interpolated using parabolic fits. The matching operation uses a window averaging scheme for each pixel with the sum of absolute differences as a dissimilarity computational measure.(see Figure 2)
- ***Verify match*** - use a left to right correspondence and verify that the right to left correspondence has a close value, otherwise, report no depth information for that pixel.
- ***Eliminate discontinuities*** - a.k.a blob filtering, remove depths that present strong discontinuities from their neigbhoring pixels.

Figure 2: Example of images processed using JPL Stereo vision pipeline

Figure 3: Stereo correlation

The stereo vision algorithm uses a number of optimization techniques to improve the overall processing speed

- **Sliding Sums** - the algorithm uses the sliding sum optimization that computes pixel intensity averages over a window. Computing such average for the next pixel

Algorithm Summary

Purpose of Algorithm:

To provide a 3D range image (or a depth map) of a scene captured through a pair of stereo images acquired from cameras that have been a priori calibrated

Inputs:

1. Two images (left and right)
2. Two camera models (left and right)
3. Tuning parameters to include: correlation window sizes, sub-sampling level (pyramid level), max disparity and noise filtering parameters

Outputs:

1. Depth image (each pixel measures corresponding depth)
2. Range image (each pixel measuring 3D (x,y,z) location of the point relative to a world frame)

Assumptions:

1. Camera models for each camera obtained through an a priori calibration procedure. Camera model include both *intrinsic* and *extrinsic* parameters. The *intrinsic* parameters represent a systematic description of the internal geometry of each camera as it relates to image formation. The *extrinsic* parameters represent the precise placement and orientation of the camera with respect to some fixed 3D coordinate system.

Figure 1: JPL Stereo vision pipeline

Computational Requirements:

1. On 1 GHZ processor, generating a range image for a 640 x 480 x 2 stereo image pair requires about 200 ms and 2 MB of RAM (verify)
2. For proper operation, the standard deviation of the stereo disparity pixel error should not exceed 1/3 pixel

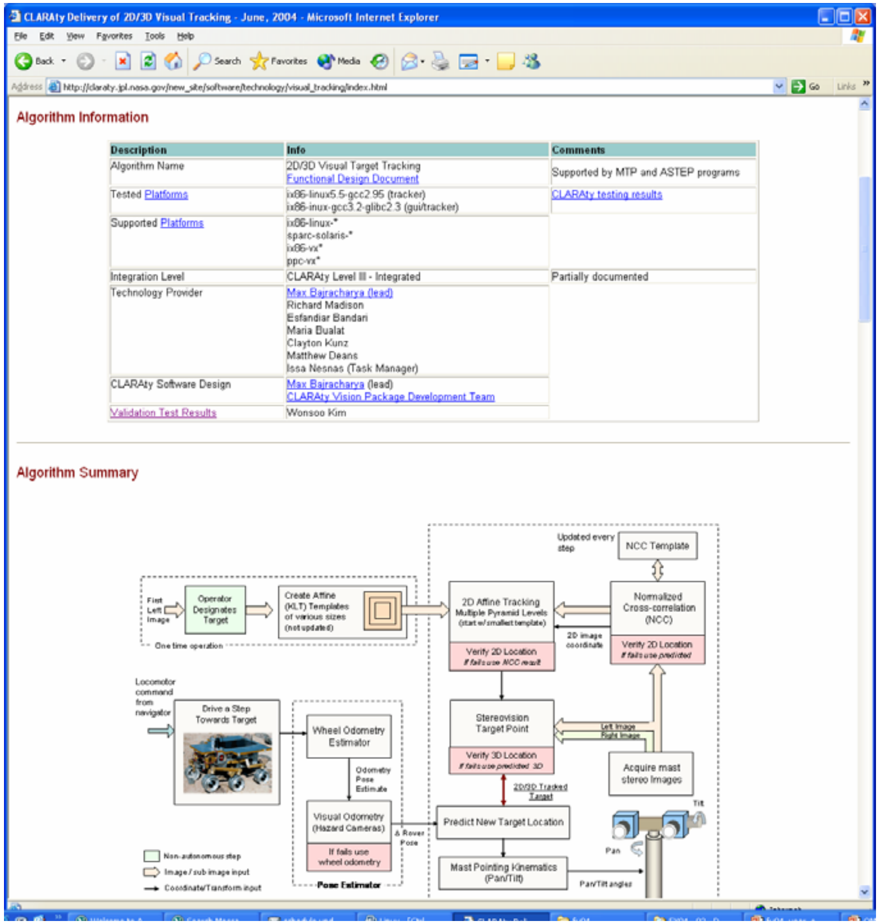
Algorithm Description

The stereo vision aglorithm uses the camera models to generate a 3D point for every pixel in the 2D image. The 3D point can be mathematically associated with a 2D image coordinates with a ray in space containing the points which project to it. The JPL stereo vision software supports the Yakimovsky-Cunningham linear camera model, CAHV, and its extensions, CAHVOR and CAHVORE. CAHV is functionally equivalent to any perspective

Specialized forward kinematics	3	JPL	I. Nesnas, H. Das	all	Dexter	Dexter arms and mast identical to

Serving the Customer

- Making a formal delivery
  - Interact with technologist to plan CLARAty integration
  - Capture algorithm and representative data sets
  - Understand and operate algorithm
  - Integrate into CLARAty and test on a rover platform
  - Do an internal shake-down test
  - Develop release documentation
  - Deliver to validation
  - Support delivery, bug fixes and feature additions
  - Maintain CLARAty test bed


CLARAty Delivery of 2D/3D Visual Tracking - June, 2004 - Microsoft Internet Explorer

http://claraty.jpl.nasa.gov/new_site/software/technology/visual_tracking/index.html

Algorithm Information

Description	Info	Comments
Algorithm Name	2D/3D Visual Target Tracking Functional Design Document	Supported by MTP and ASTEP programs
Tested Platforms	ix86-linux5.5-gcc2.95 (tracker) ix86-inux-gcc3.2-glibc2.3 (gui/tracker)	CLARAty testing results
Supported Platforms	ix86-linux-* sparc-solaris-* ix86-vx* ppc-vx*	
Integration Level	CLARAty Level III - Integrated	Partially documented
Technology Provider	Max Bajracharya (lead) Richard Madison Esfandiar Bandari Maria Bualat Clayton Kunz Matthew Deans Issa Nesnas (Task Manager)	
CLARAty Software Design	Max Bajracharya (lead) CLARAty Vision Package Development Team	
Validation Test Results	Wonsoo Kim	

Algorithm Summary

Significant Events

Level I – framework for single-cycle instrument placement

Level II – framework for comparing pose estimators

Significant Event – Single Cycle Instrument Placement

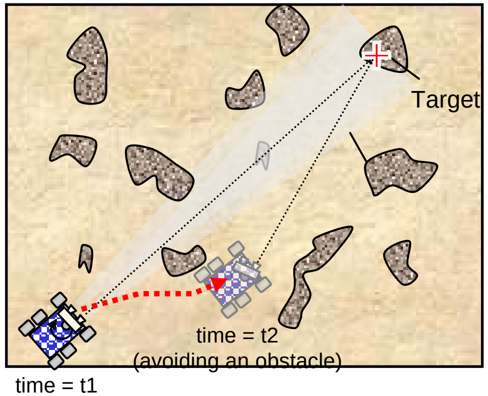
- Provided a framework for end-to-end single-cycle instrument placement (SCIP) on Rocky 8 (Level I milestone)
- Demonstrated integration of the following technologies:
  - Visual 2D/3D Tracking (JPL - RMSA)
  - Morphin Navigator (CMU)
  - Wheel odometry pose estimator (JPL)
  - Camera handoff (JPL)
  - Rover base placement (JPL – IS/MSL)
  - 5DOF manipulation (JPL – MTP/MSL)
  - Commanding through Maestro
- Importance:
  - SCIP increases science return by saving the mission 2 sols out of 3 per placement. Key component for multiple instrument placements.
  - Framework to plug in different technologies for validation of end-to-end capability

Designating a target

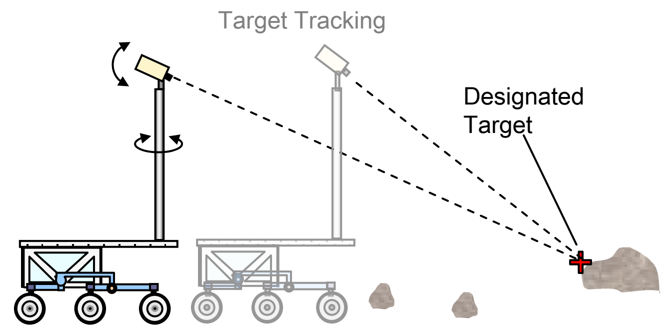
Rocky 8 tracking and navigating

__Max Bajracharya__ (lead), Antonio Diaz Calderon,
Won Soo Kim, Mark Powell
(Joint effort with MSL manipulation and Maestro tasks)

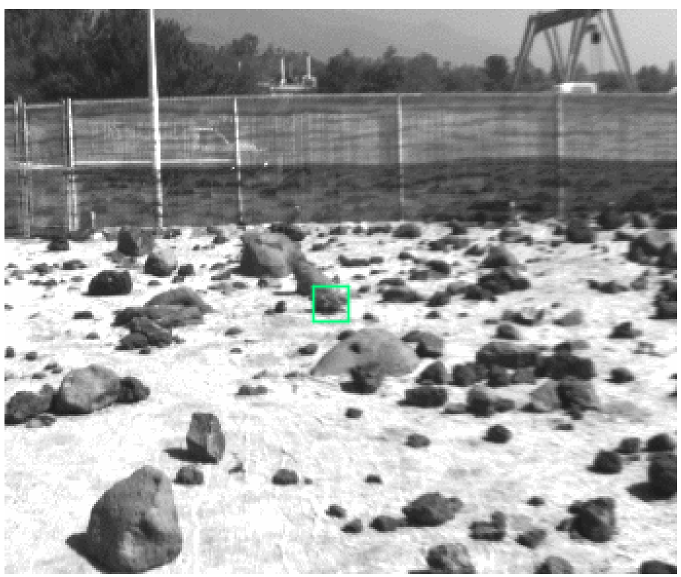
Level I Milestone - Key Challenges



(a)

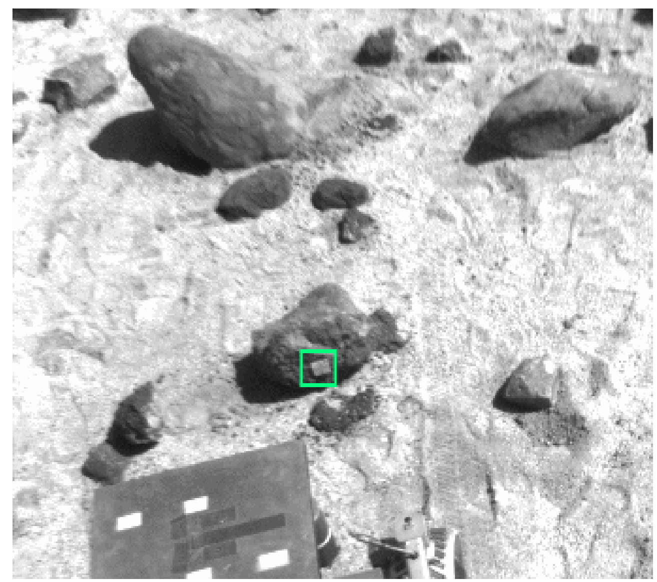


(b)



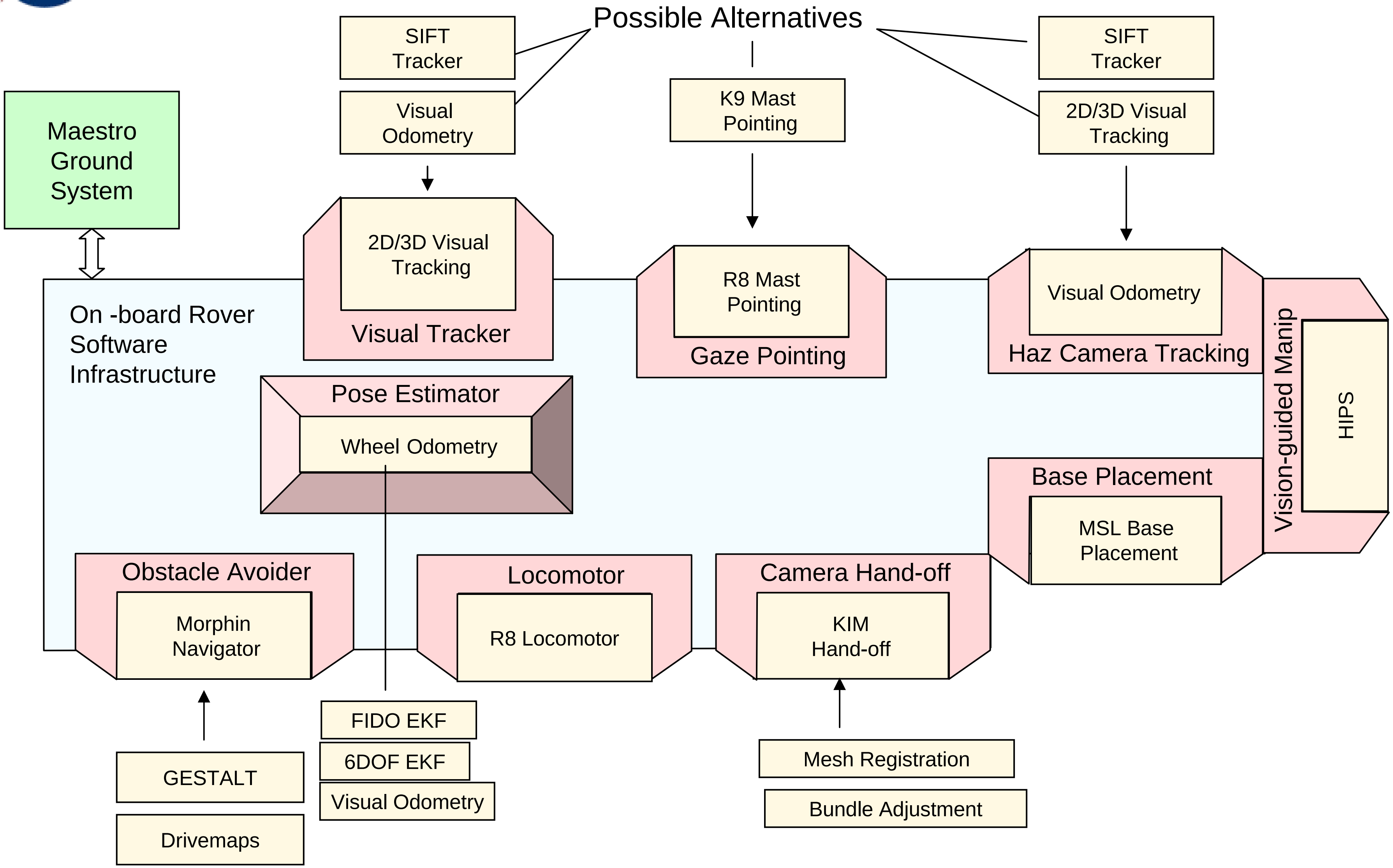
1st Frame

Changes in FOV



37th Frame after 10 m

Framework for Single-cycle Instrument Placement



Video of Single-cycle Instrument Placement

Element	Provider	Comments
Rover takes panorama and sends images to Maestro	CLARAty	
Maestro displays images and user designates a target point. Host sends selected target to rover	WITS/Maestro Task (Norris, Powell)	
Rover uses 2D/3D visual tracking from navigation cameras (45° FOV) to track target from 10 – 2 m	Visual Target Tracking (Nesnas, Bajracharya, Madison, ARC)	
Rover uses Morphin navigator to avoid obstacles	CLARAty (Simmons)	
Rover tracks using mast pointing while avoiding obstacles and estimating pose	CLARAty (Bajracharya)	
At 2 – 3 m, rover hands-off target from navigation cameras to hazard cameras using first: 1. Kinematic chain from calibrated mast 2. Image-based matching to refine new target location	1. Instrument Placement (Kim) 2. CLARAty (Bajracharya) – unplanned effort	Hand-off technology from Ohio State did not operate properly on rover images. Video demonstrates manual hand-off due to lack of robustness of current on-board algorithm. ARC mesh registration is a possible alternative
Rover can use visual odometry to estimate pose from 3 m – 0.5 m using hazard cameras – video shows just wheel odometry for this segment	Slope navigation (Matthies, Cheng, Helmick)	Algorithm failed to produce reliable and accurate estimates on images from Rocky 8 hazard cameras.
Rover base placement	MSL Manipulation (Backes, Calderon)	
5DOF arm deployment	MSL Manipulation (Backes, Calderon)	
Vision-guided manipulation using HIPS	MSL Manipulation (Backes, Robinson)	At the time the video was acquired, this technology was not integrated onto the rover.

Some delays attributed to late integration of new 5DOF arm on the rover

Significant Event – Comparing Pose Estimators

- Provided a framework to compare five pose estimators.
- Verified by running on real rover data:
  - Sojourner
  - Rocky 7 with sun sensing
  - FIDO 3DOF EKF
  - Simplified version of 6DOF EKF
  - Wheel odometry
  - Visual Odometry
- Mission Importance:
  - Framework to compare algorithms
  - Demonstrates SOA and future potential

Rocky 8 (front) and FIDO (back)

Measuring Ground Truth using Total Station

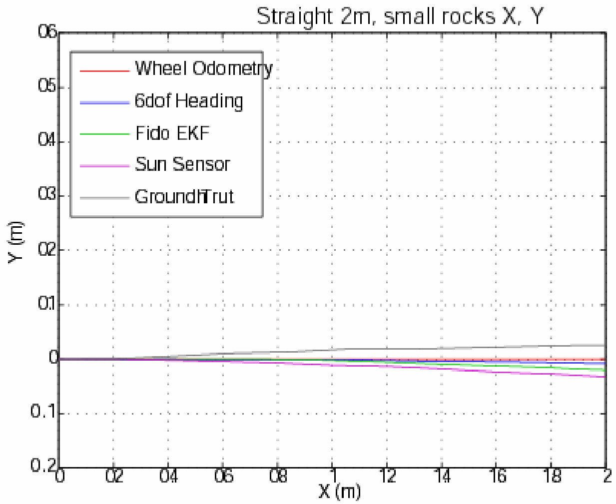
Dan Gaines *(lead), Antonio Diaz Calderon*

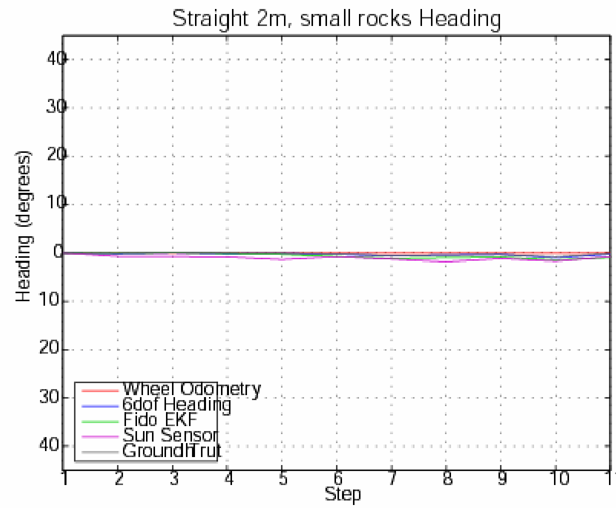
Level II Milestone - Comparing Pose Estimators

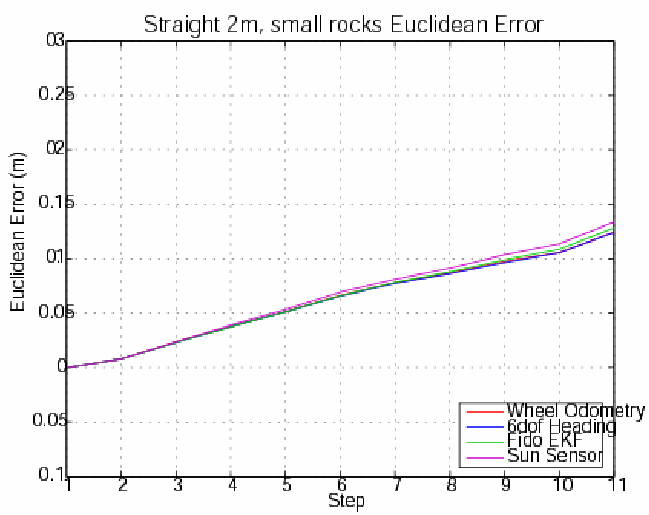
- *Comparison done to verify correctness and not to validate performance*
- Pose Estimators:
  - **Sojourner:** integrates z-axis gyro with wheel odometry (flat terrain)
  - **FIDO EKF:** filters z-axis gyro bias & combines wheel odometry (flat terrain)
  - **Sun sensor:** wheel odometry with sun sensor heading corrections
  - **6DOF EKF:** *incomplete version* - 3-axis IMU with flat terrain kinematics
  - **Wheel odometry:** integrated delta encoders
  - **Visual Odometry:** uses hazard cameras to estimate ego-motion
  - **Ground Truth** – measured using a total station at every interval
- Tested on four runs
  - 2 m straight line traverse over small rocks
  - 2 m straight line traverse over larger rocks
  - 2 m arc with 0.5 rad heading change over small rocks
  - 2 m arc with 0.5 rad heading change over large rocks

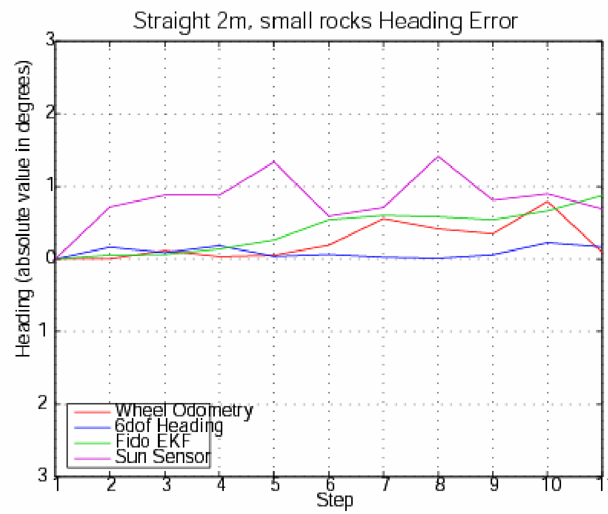
Heading relative to beginning of move
IMU mount not finely calibrated relative to rover frame

Pose Estimators – (a) 2 m straight; small rocks

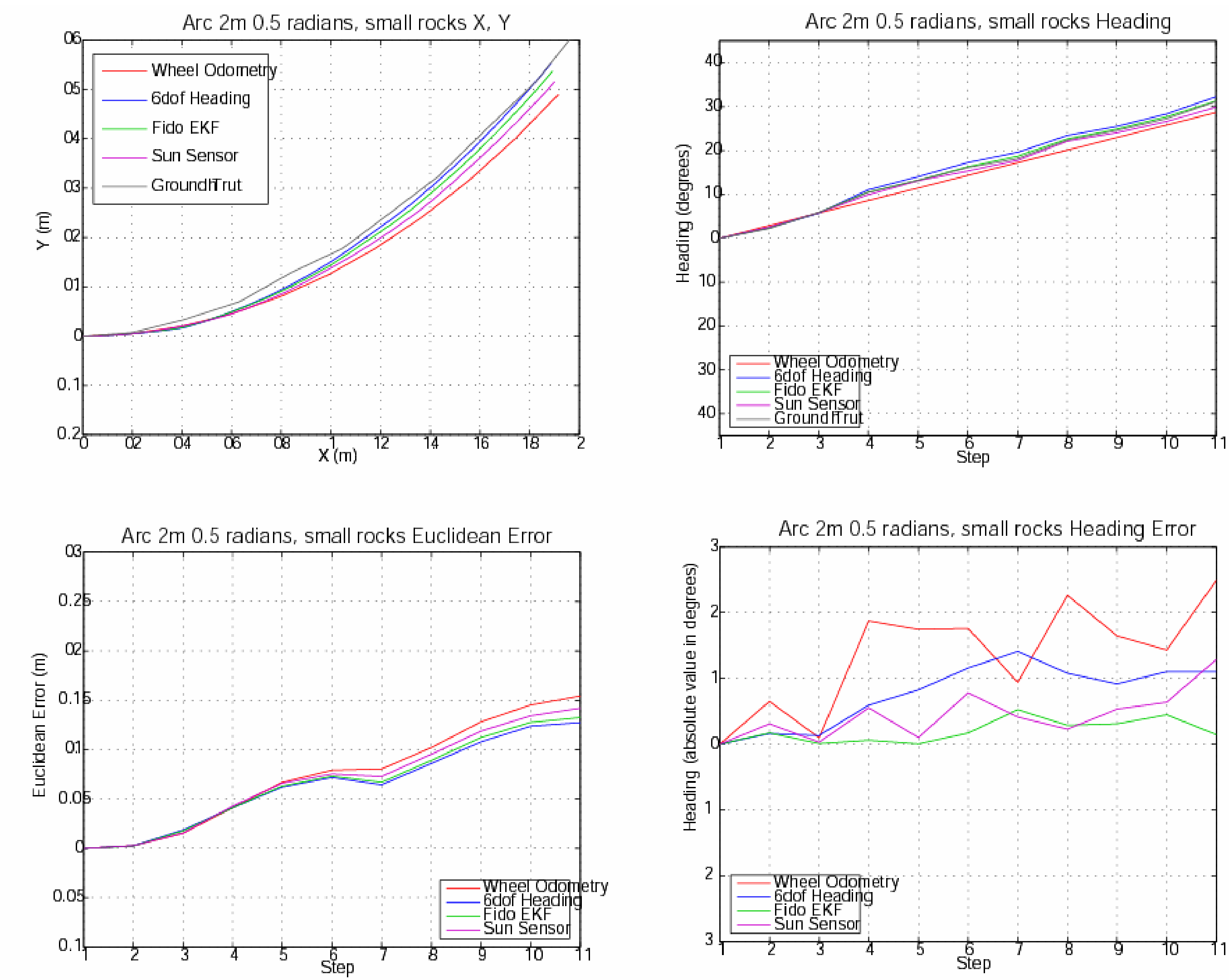




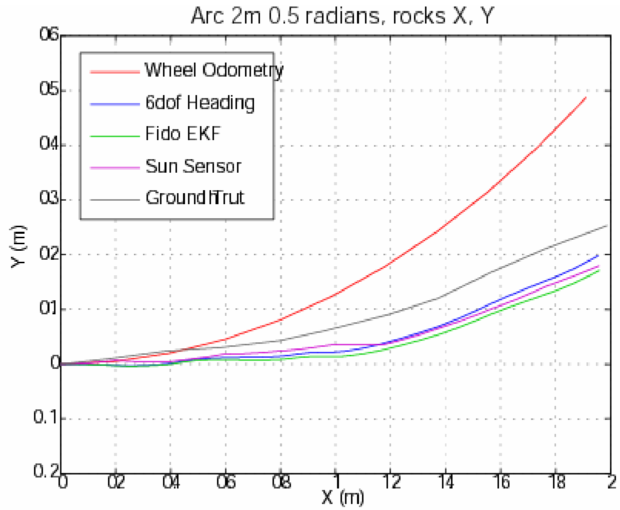


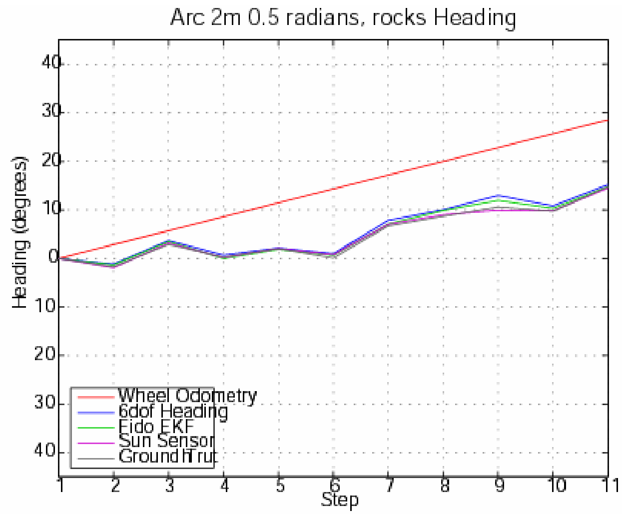


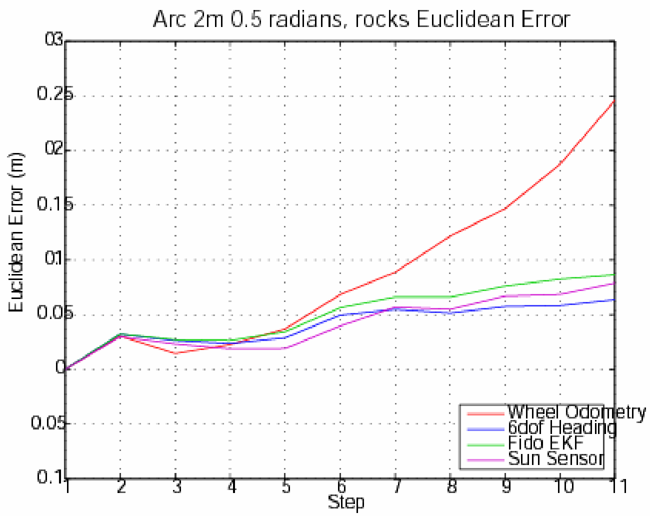
Pose Estimators – (c) 2 m arc; small rocks

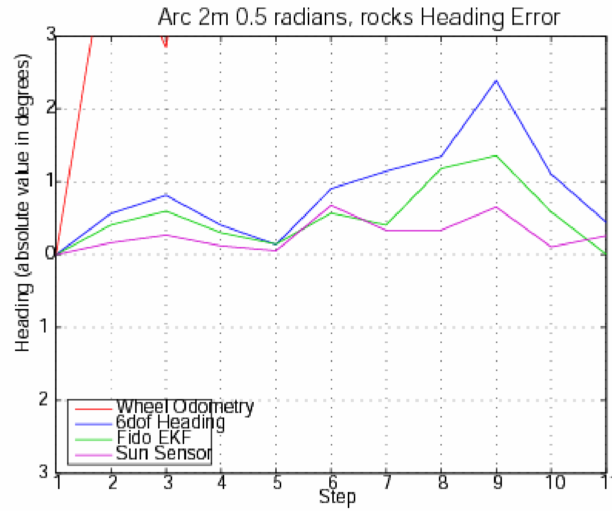


Pose Estimators – (d) 2 m arc; large rocks









Pose Estimators – Some Observations

- Performance of all estimators except wheel odometry is comparable
- A gap exists between most pose estimators and ground truth – there is a significant potential for research to close that gap
- Occlusions from fixed mast impact sun sensor

Deliverables and Technical Progress

Status of Navigation Algorithms in CLARAty

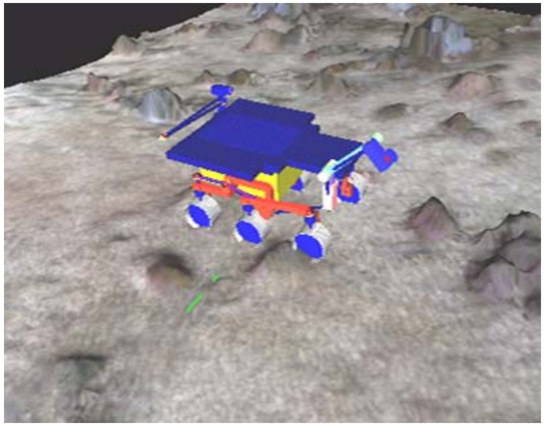
Description	Morphin	MER GESTALT	GESTALT V1.0	Drivemaps
Integration Status	Refactored	Encapsulated *(includes its own stereo)*	Encapsulated *(uses CLARAty stereo version)*	Encapsulated *(uses CLARAty stereo version)*
Platforms Tested	Rocky 8 FIDO ROAMS Simple Sim	ROAMS	Rocky 8	Simple Sim
Validation Status	Delivered to LT	-	-	-
Future Plans	-	Test on Rocky 8	Obsolete	Generalize and test on FIDO, Rocky 8 and ROAMS

Simple Sim – a simple and fast CMU simulator that generates binary terrain for navigation testing

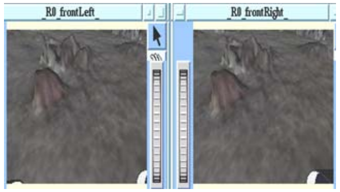
MER GESTALT with ROAMS

- Encapsulated latest uploaded MER version of GESTALT (R9.0)
- New version (R9.1) still under development. We plan to upgrade once available
- Adapted navigator to ROAMS
- GESTALT runs on the Rocky 8 bench top and interfaces with ROAMS
- Successfully avoided obstacles
- Reached goal on benign terrain

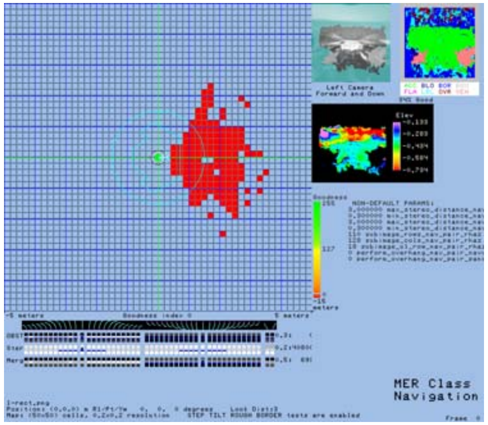
- Future Work
  - Further test and tune the adaptation
  - Port to Linux
  - Adapt to a real rover
  - Prepare for validation



ROAMS FIDO simulation



Front Hazard Stereo images

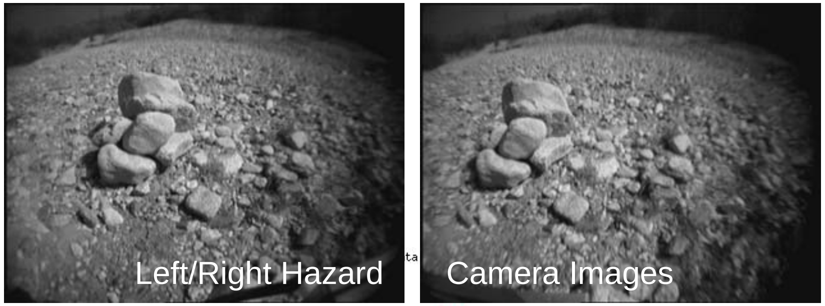


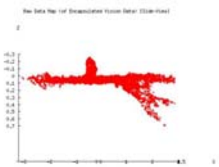
Example of a GESTALT Goodness Map (does not correspond to above images)

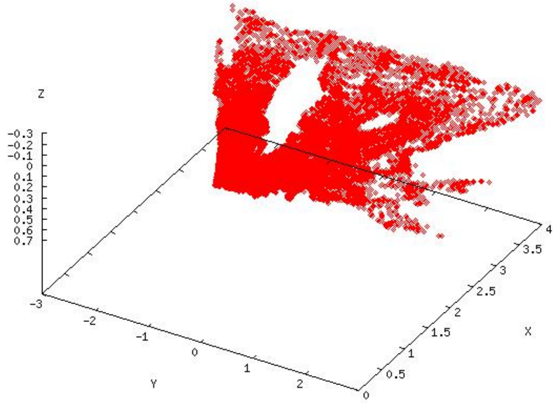
Drivemaps Navigator

- Encapsulated FIDO Drivemaps navigator into CLARAty
- Tested elements on real field data
- Preliminary limited testing of behavior using a simple simulator

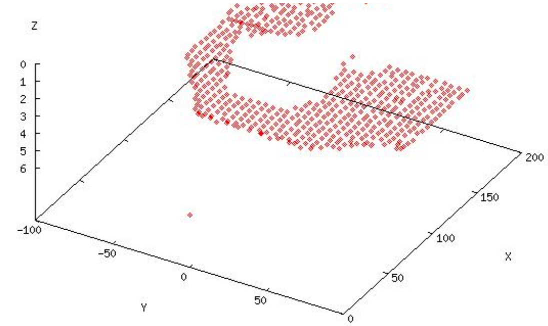
- Future Work
  - Generalize implementation to be rover independent
  - Further test for anomalies
  - Port to Linux
  - Adapt to a real rover
  - Prepare for validation


Left/Right Hazard Camera Images





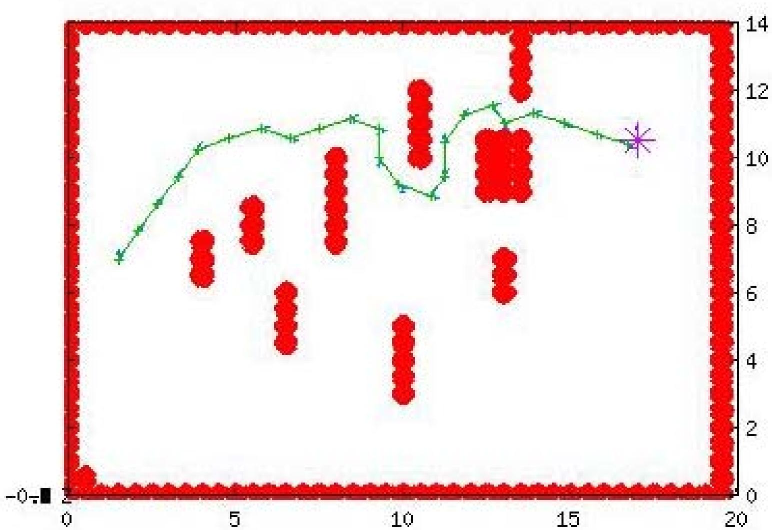
Stereo Point Cloud (above side view)



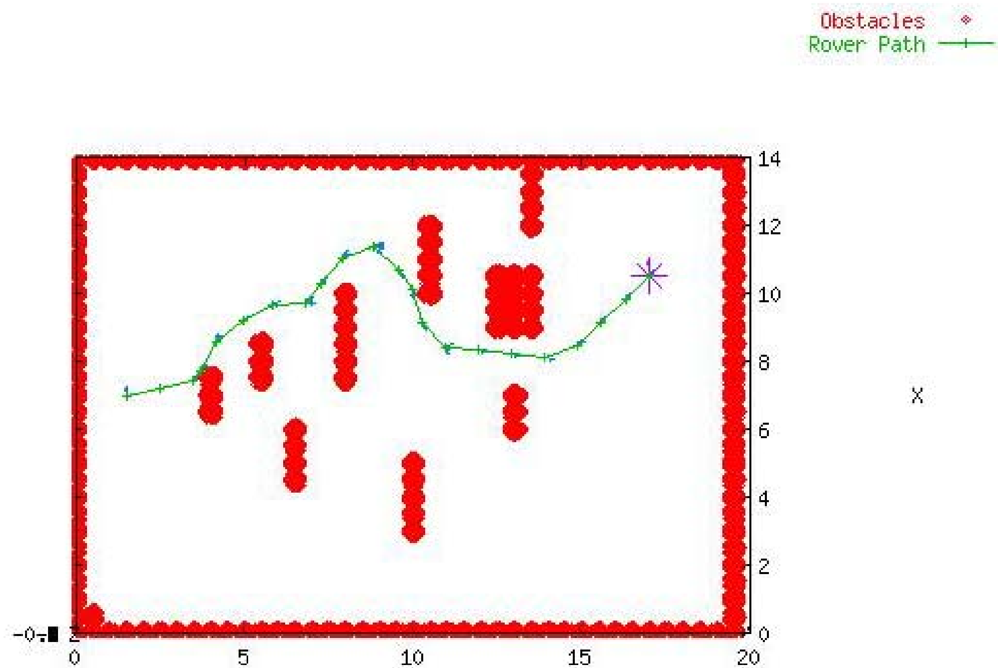
Status Map

Drivemaps vs Morphin Navigators

- Ran experiments with Drivemaps and Morphin using Simple Simulation (binary obstacle terrain)
- Navigation logic generates different paths to reach goal



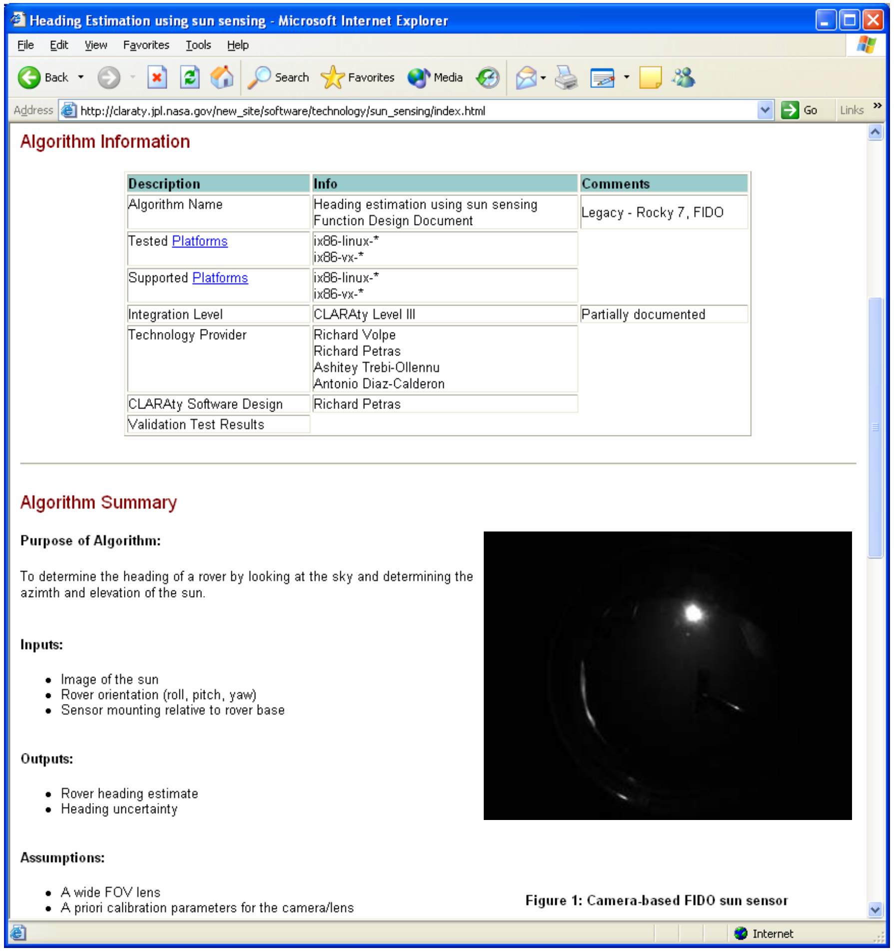
Morphin Traverse



Drivemaps Traverse

Sun sensor Heading Estimator

- Implemented a new sun centroid finder
- Implemented new morphological operators (erosion and dilation for two different template sizes)
- Added eccentricity calculation to improve sun detection
- Implemented exposure control for Rocky 8 cameras to improve image quality
- Future Work:
  - Add uncertainty to sun vector
  - Adapt and test on FIDO



Heading Estimation using sun sensing - Microsoft Internet Explorer

http://claraty.jpl.nasa.gov/new_site/software/technology/sun_sensing/index.html

Algorithm Information

Description	Info	Comments
Algorithm Name	Heading estimation using sun sensing Function Design Document	Legacy - Rocky 7, FIDO
Tested Platforms	ix86-linux-* ix86-vx-*	
Supported Platforms	ix86-linux-* ix86-vx-*	
Integration Level	CLARAty Level III	Partially documented
Technology Provider	Richard Volpe Richard Petras Ashitey Trebi-Ollennu Antonio Diaz-Calderon	
CLARAty Software Design	Richard Petras	
Validation Test Results		

Algorithm Summary

Purpose of Algorithm:

To determine the heading of a rover by looking at the sky and determining the azimth and elevation of the sun.

Inputs:

- Image of the sun
- Rover orientation (roll, pitch, yaw)
- Sensor mounting relative to rover base

Outputs:

- Rover heading estimate
- Heading uncertainty

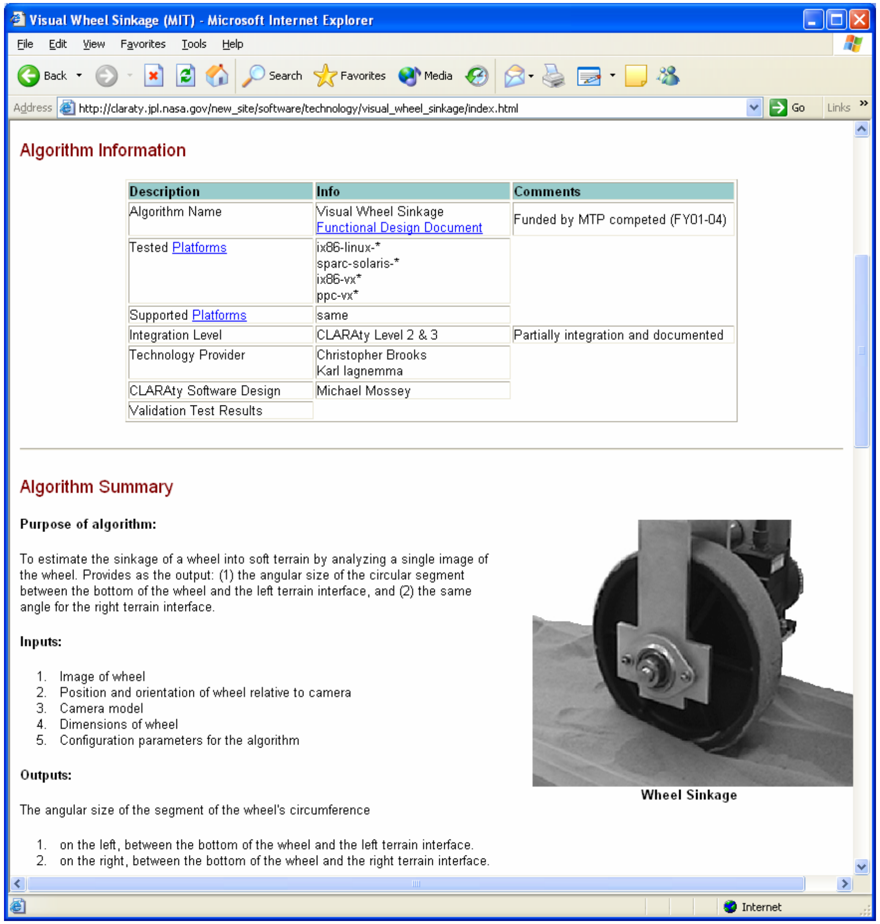
Assumptions:

- A wide FOV lens
- A priori calibration parameters for the camera/lens

Figure 1: Camera-based FIDO sun sensor

Visual Wheel Sinkage

- Translated MIT's visual wheel sinkage into CLARAty
- Tested on all supported platforms (VxWorks and Linux)
- Tested against images provided by technologist
- Compiled and posted documentation provided by technologist
- No available rover setup for further testing



CLARAty Test bed

Supported Platforms

Rocky 8

VxWorks | x86 | ppc

JPL

K9

Linux | x86

Ames

Rocky 7

VxWorks | ppc

JPL

FIDO

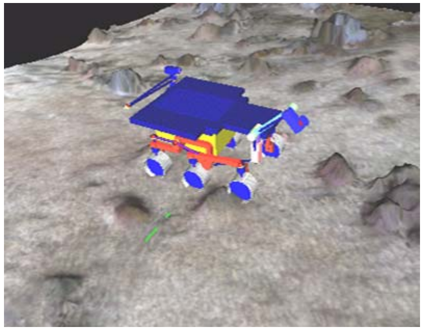
VxWorks | x86

JPL

ATRV

Linux | x86

CMU

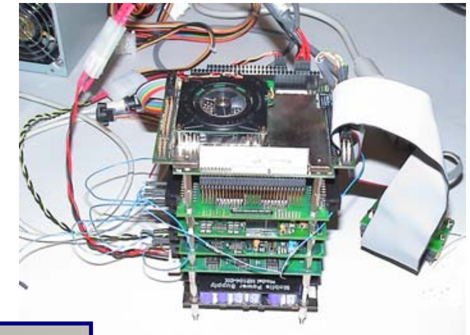


ROAMS

Linux

JPL

New in the CLARAty Test Bed



FIDO2 Stack

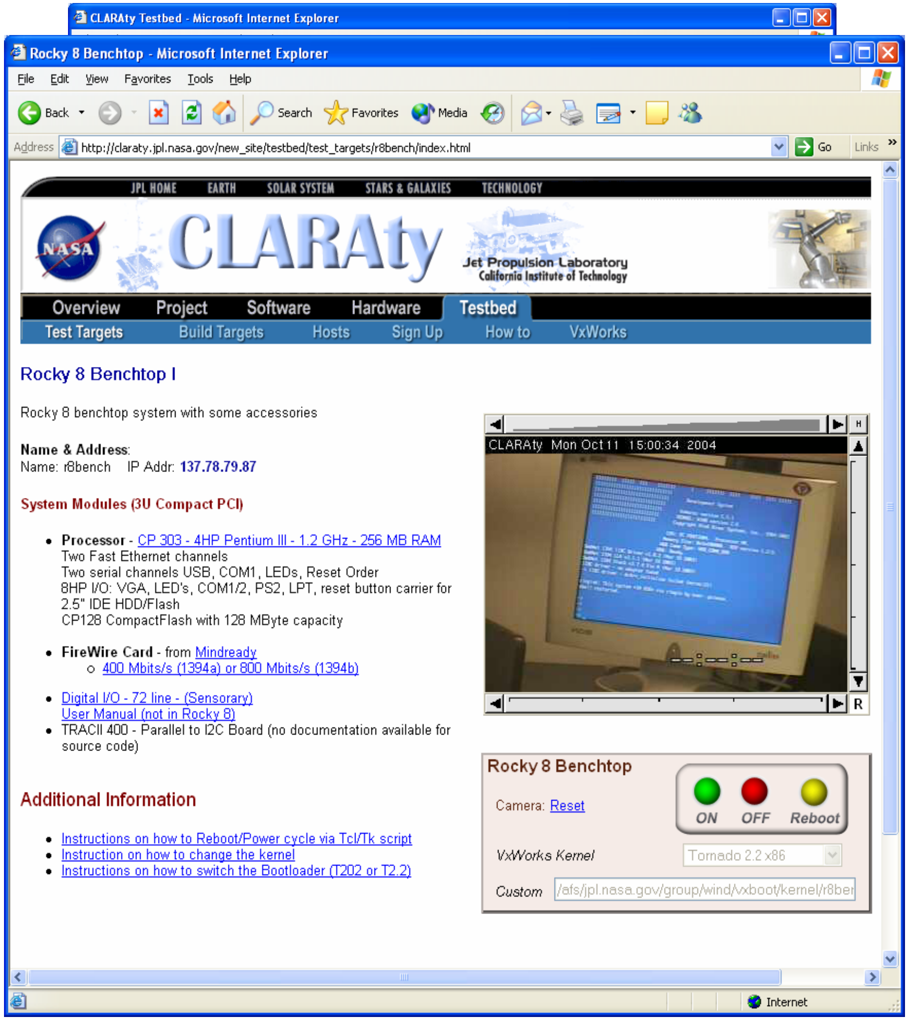
ATRV Jr.

Dexter Manipulator Bench top

Rocky 8 PPC Bench top

CLARAty Test Bed

- Added two new targets:
  - Rocky 8 bench top with PPC for MDS/MSL
  - FIDO2 stack – hybrid of Rocky 8 and FIDO
- Used by:
  - CLARAty Developers
  - MSL Manipulation task
  - Validation tasks
  - MDS/MSL
- Remote Access
  - Web camera
  - Remote power cycle



LM629 Motion Control Board

- Delivered LM629 Motion Control board to MSL manipulation task
  - 16 axes motor controllers/board
  - Support for multiple boards
  - Current sensing
  - H-bridge braking
  - Analog interface for potentiometers

Publications to Date

- Publications:
  - M.G. Bualat, C.G. Kunz , A.R. Wright, I.A. Nesnas, "Developing An Autonomy Infusion Infrastructure for Robotic Exploration," Proceedings of the 2004 IEEE Aerospace Conference, Big Sky, Montana, March 6-14, 2004. pdf (14 pages, 0.7MB)
  - R. Volpe, "Rover Functional Autonomy Development for the Mars Mobile Science Laboratory," Proceedings of the 2003 IEEE Aerospace Conference, Big Sky, Montana, March 8-15, 2003. pdf (10 pages, 1.2MB) C. Urmson, R. Simmons, "Approaches for Heuristically Biasing RRT Growth," Proceedings IROS 2003, October, 2003
  - I.A. Nesnas, A. Wright, M. Bajracharya, R. Simmons, T. Estlin, Won Soo Kim, "CLARAty: An Architecture for Reusable Robotic Software," SPIE Aerosense Conference, Orlando, Florida, April 2003. (730 KB)
  - I.A. Nesnas, A. Wright, M. Bajracharya, R. Simmons, T. Estlin, "CLARAty and Challenges of Developing Interoperable Robotic Software," invited to International Conference on Intelligent Robots and Systems (IROS), Nevada, October 2003. (410 KB)
  - C. Urmson, R. Simmons, I. Nesnas, "A Generic Framework for Robotic Navigation," Proceedings of the IEEE Aerospace Conference, Montana, March 2003. (8 pages, 730KB)
  - C. M. Chouinard, F. Fisher, D. M. Gaines, T.A. Estlin, S.R. Schaffer, "An Approach to Autonomous Operations for Remote Mobile Robotic Exploration," Proceedings of the IEEE Aerospace Conference, Montana, March 2003 (277 KB)
  - T. Estlin, F. Fisher, D. Gaines, C. Chouinard, S. Schaffer, I. Nesnas, "Continuous Planning and Execution for an Autonomous Rover," Proceedings of the Third International NASA Workshop on Planning and Scheduling for Space, Houston, TX, Oct 2002. (168 KB)

Backup slides

Measuring Success or Failure

We succeed **IF** we:

- Significantly reduce integration time of new technology software onto real robotic systems
- Support multiple platforms with different hardware architectures
- Provide a service that is enabling for technologists
- Simplify the development/integrate/debug/test cycle for current and next generation NASA rovers
- Have people other than the developers using and "*liking*" the system